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EFFECTS OF HUMAN FACTORS ON APOLLO SYSTEM PERFORMANCE FOR LUNAR ORBIT RENDEZVOUS AND TWO-MAN DIRECT FLIGHT MODES [U]

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FOREWORD

This report has been prepared by the Space Systems Division of the Martin Company in compliance with NASA Contract NASw-534, "Human Factors Comparison of Direct and LOR Modes for Project Apollo Mission." Supplementary data which is not required by the contract but which will be beneficial to NASA is submitted under separate cover as Engineering Report No. ER 12750.

CONTENTS

I. INTRODUCTION AND APPROACH

Mission success and crew survival are prime considerations in the Apollo program of manned lunar expeditions. Accordingly, reliability and safety are being given major emphasis in both NASA and industry studies of Apollo systems.

The large background of experience and data which supports the estimation of equipment reliability does not exist in the area of crew performance reliability. But the reliability of a man-machine system is dependent on the degree to which man can successfully perform his assigned tasks. It is therefore important to make maximum use of the available applicable data to assess crew performance and its influence on the Apollo mission. The present study is an attempt to determine, for two modes of manned lunar flight, the effects of crew performance on system reliability. The two modes investigated are the lunar orbit rendezvous (LOR) and the two-man direct flight (DF). Although the study is primarily directed at exploring the possibility that crew involvement may affect the relative desirability of these two approaches, it is of potential general interest in that it represents an initial step toward the development of methodology for consideration of human reliability in systems engineering.

The six-week program was conducted by the Martin Company, Space Systems Division, for the Office of Systems (OS), Office of Manned Space Flight, NASA Headquarters in accordance with Refs. 1, 2 and 3. The importance and complexity of the subject warrant treatment in far greater depth than was possible in the six-week period. Thus, although some of the results have necessarily been presented in precise quantitative form, they can only be regarded as indicative of trends.

Clearly, the significant problem faced in this brief investigation was that of analyzing crew tasks and expressing crew performance as a quantitative system reliability input. Design and system analyses were conducted only as necessary to provide the framework for determination of operational functions, identification of subsystems, definition of man-machine relationships and estimation of reliability. For the DF vehicle, gross preliminary design was accomplished in accordance with ground rules provided by the Office of Systems; the LOR configuration was based largely on Martin's previous design effort in connection with the Apollo and Lunar Excursion Module proposals.

Basic equipment-only reliability estimates were established by the Office of Systems. These were modified to reflect fundamental design modifications and to permit consideration of major subsystems (e.g., power supply and environmental control systems) which were not included in the OS data. The modified estimates represent the reliability of a fully automatic system for each mode. Man-machine relationships were next established on the basis of mission, function, design, and crew task analyses, and crew functions were assigned accordingly. System reliability was then re-estimated, initially on the assumption of 100% crew performance and finally using crew performance as estimated from human factors consideration. Where the results indicated nonoptimum use of the crew, man-machine relationships were modified and the process was repeated.

The study has been restricted primarily to "nominal" missions, since any generalization based on malfunction and emergency considerations would require analysis of an impractically large number of possible failure combinations. Several representative emergencies have been examined, however, and are discussed separately. Repair and maintenance considerations are also treated separately.

The analysis of human performance in terms of reliability over extended time periods is a most difficult task even in a laboratory situation. The factors which appear to contribute to the reliability of performance are numerous and nonsystematized within the experimental literature. An additional problem appears to be the subject population utilized in the studies performed. No valid correlation can be expected between the experimental tracking task performance of a college sophomore or an institutionalized patient and the in-flight tracking performance of an astronaut. The extensive operational experience, skills, and attitudes gained by the astronauts prior to selection, and the high motivation developed prior to and during a flight, cannot be represented in an experimental situation with an "average" population.

These considerations have been observed in a number of long duration space flight simulations. A recent study (Ref. 4) using a 15-day confinement period and two operational B-52 crews indicated the effect of motivation on simulated crew performance. The volunteer crew was less affected by the confinement conditions than the nonvolunteer crew. Another study on a 7-day simulated lunar orbit mission (Ref. 5) indicated the importance of crew composition as to the occurrence of performance and personality effects. The test pilot crew member was less affected by the confinement conditions than the other two individuals trained in scientific disciplines. In another recently completed study utilizing test pilot personnel (Ref. 6), no significant performance effects were noted due to sensory deprivation or confinement during missions as long as seven days.

Though high motivation and crew composition are of obvious importance in attempting to ascertain the reliability of performance on an a priori basis, other experimental variables are also important. The results of Ref. 6 clearly indicated the importance of a good display system, and crew training and familiarization, to the reliability of task performance after extended periods of flight. Another very important variable in the measurement of crew reliabilities is the realism of the tasks utilized. Generalization of data from simple psychomotor tasks to the tasks anticipated for lunar flights is difficult or almost impossible. Therefore, the performance to be evaluated as to crew reliability must be based on realistic tasks, performed in a realistic time-trajectory relationship. A review of the available literature revealed that only two studies have utilized tasks based on realistic lunar trajectories (Refs. 5 and 6).

With the above-mentioned difficulties and the importance of the indicated factors, a valid estimate of crew reliability for any long term space mission can only be made from data obtained from simulator studies encompassing, to some extent, each of these factors. However, the realism of actual flight is still not present and the data must be judiciously generalized to actual flight situations. Therefore, a major assumption of the present study was to consider only data which were obtained in a realistic situation with an astronaut or equivalent population. This assumption restricted the available data to some extent, but it also provided a more valid estimate of performance reliability.

Degradation of crew performance during an extended lunar mission may easily be suspected from an inspection of the literature on confinement and sensory deprivation and a description of the lunar systems. The literature indicates that a number of factors in man-machine systems warrant attention in consideration of crew performance deterioration:

(1) Long term monitoring performance.

(2) Restrictive volume.

(3) Task complexity.

(4) Biomechanical or environmental stress.

(5) Anxiety or general psychological stress.

(6) Continuous complex task performance.

(7) Fatigue.

(8) Sensory deprivation.

As will be discussed later in the report, Items (6), (7) and (8) were eliminated from the list of significant factors for the present study--Items (6) and (7) by task assignment and duty cycle and Item (8) by analysis of pertinent simulation results.

The methods of analysis of these factors, the estimation of crew performance reliabilities, and the incorporation of the results into overall system reliability estimation, are all discussed in appropriate sections of the report.

II. CONFIGURATIONS

The reference configurations for the LOR and DF modes are shown in Figs. II-1 and II-2. Onboard systems are covered in Section III.

For both modes, it was assumed that the launch vehicle has a maximum effective payload capability of 90,000 lb to escape. This includes spacecraft, spacecraft adapters and necessary fairings, and launch escape system. Figure II-3 contains the mission profiles, the velocity change (ΔV) requirements and the identification of propulsion units employed in the various thrusting phases. The ΔV requirements for the LOR mission were based on information obtained from the Lunar Excursion Module (LEM) RFP MSC-63-181P, and the LEM Bidders' Conference technical briefing of 15 July 1962. For the DF mode, the ΔV values were modified to reflect the reduced requirements associated with elimination of the rendezvous considerations.

A. SPACECRAFT DESIGN

1. LOR

The LOR spacecraft design is based on LEM and Command Module layouts proposed to NASA by the Martin Company. As shown in Fig. II-1, the spacecraft consists of a Service Module (SM), a Command Module (CM), and the LEM, with an overall gross weight of 87,300 lb. Storable propellants are employed throughout; the unstaged SM has a 45,000-lb usable propellant capacity.

The LEM payload weight is 3380 lb, not including the crew. Total LEM weight is 22,000 lb. The lightweight aluminum skin structure is possible because the LEM is contained within the CM/SM adapter throughout the launch phases and the LEM is therefore not subjected to aerodynamic forces or high acoustic levels. The LEM propulsion system is sealed until lunar orbit is attained; the last stage of the launch vehicle is used to stabilize the LEM during the initial repositioning phase of the LOR mission.

The design weight for the CM and its related SM-borne equipment is 13,750 lb. Available data indicate that current Apollo weight estimates show approximately 12,000 lb for this combination. Thus, the spacecraft design shown can be considered to provide for an 11% growth in systems weight

$$\left(\frac{13{,}750 + 3380}{12{,}000 + 3380} - 1 = 0.11\right).$$

The volumes available for crew use are 233 cu ft (approximately 78 cu ft per man) in the CM and 106 cu ft (53 cu ft per man) in the LEM. Display areas are 15 sq ft in the CM and 7 sq ft in the LEM.

2. DF

In accordance with Ref. 2, preliminary design of the DF spacecraft, Fig. II-2, was based on a 120-in. diameter CM geometrically similar to the three-man CM. Onboard system weights for the two-man eight-day mission were derived assuming the same type of systems as for the LOR mode (i.e., systems under development in the present

Apollo program). A weight allocation for specific radiation shielding was assumed as two-thirds of the shielding weight provided in the Martin three-man Apollo CM design, or 466 lb.

The estimated CM-plus-equipment weight was 8932 lb. For consistency with the LOR design philosophy, a payload weight growth allowance of approximately 10% was included, and the remainder of the spacecraft configuration consisting of a lunar landing module and a lunar launch or SM, was sized for a 9800-lb payload.

Several main propulsion approaches were considered for the DF spacecraft; pressure-fed storable-propellant attitude control systems were used in all cases. Estimated weights for five configurations were as follows:

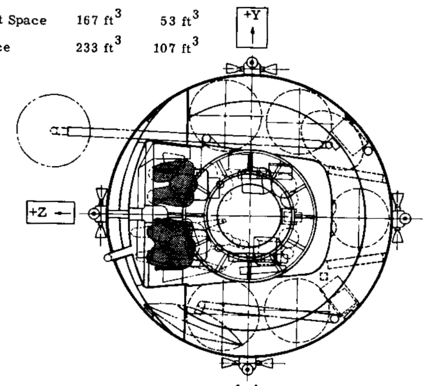
Configuration	Service Module	Landing Module	Gross Weight (lb)
A	Storable, pressure fed	Storable, pressure fed	186,000
B	Storable, pressure fed	LOX-hydrogen, pump fed	123,000
C	LOX-hydrogen, pressure fed	LOX-hydrogen, pressure fed	97,000
D	LOX-hydrogen, pressure fed	LOX-hydrogen, pump fed	93,000
E	LOX-hydrogen, pump fed	LOX-hydrogen, pump fed	87,800

In view of the 90,000-lb launch vehicle payload limitation, Configuration E was selected as the study system, and pump-fed LOX-hydrogen main propulsion systems were employed in both the SM and the landing module.

The CM size limitation results in an available crew space of 80 cu ft, or 40 cu ft per man. A volume of 103 cu ft remains for equipment storage. It was assumed that this volume would be adequate to contain the necessary equipment, although this would require a higher equipment density than that achieved in the three-man CM design studies.

As discussed in Chapter IV, the crew space limitation is a major factor affecting crew performance. Although several new CM design approaches might be considered for increasing available crew volume, such design effort was beyond the scope of this study. For a CM geometrically similar to the present design, it is estimated that provision of 70 cu ft of space per man would require a size increase in diameter to approximately 132 in., and a corresponding increase in spacecraft weight to a total exceeding the launch vehicle capability.

	Apollo	LEM
Display Area	15 ft^2	7 ft^2
Equipment Space	167 ft^3	53 ft^3
Crew Space	233 ft^3	107 ft^3



Stage	Use	ΔV	Propellant Wt (lb) Basic	Engine Thrust (lb)	Stage Weight (lb)
Command Module					13,750
Service Module	LEM rendezvous, lunar orbit ejection. Trans-earth correction	4,913	14,000	22,000	50,000
	Translunar correction, lunar orbit injection, plane change	3,883	27,200		
LEM (less men)	Deorbit, brake, hover, land, takeoff, rendezvous with CM	14,620	15,200	8800* 3000*	21,560
Adapter					2,000
Total wt					87,310

LOR Payload Breakdown Weight (lb)

		CM/SM		LEM
CM/Launcher-Structure		3,630		507
CM/Launcher-Equipment				
Reaction control system		462		403
Landing system		534		--
Electrical system		350		141
Environmental control		542		270
Instruments and displays		245		98
Furnishings and equipment		489		122
Crew and suits	(1)	222	(2)	444
Communications		105		118
Instrumentation		252		173
Scientific equipment		--		32
Guidance and navigation		454		333
Stabilization and control		144		144
Radiation protection		700		--
Total		8,129		2785
SM/Lander-Equipment				
Electrical		1,713		335
Environmental control		498		383
Communications		162		46
Guidance and navigation		60		31
Attitude control		729		--
Furnishings		--		49
Instrumentation		--		33
Scientific equipment		--		218
Separation system		30		23
Total		3,192		1118
Payload Total		11,321		3903

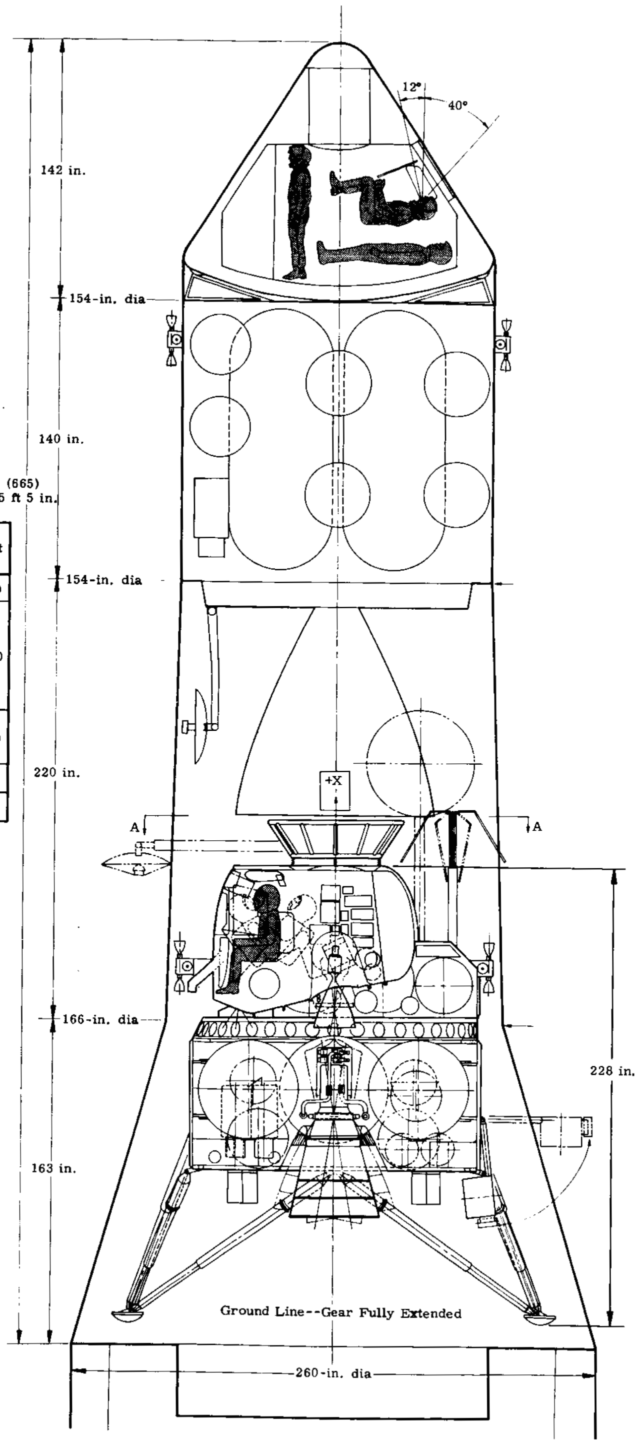
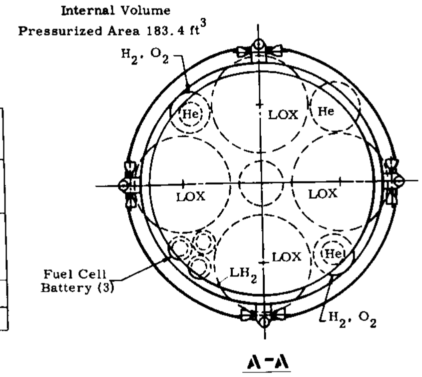


Fig. II-1. LOR Configuration

[redacted]

Stage	Use	ΔV	Propellant Type	Propellant Weight (lb)	Eng Thrust (lb)	Stage Weight (lb)
II	Lunar takeoff to lunar orbit, lunar orbit ejection, transearth corr	10,613	LOX, LH_2	15,000	11,500	18,900 Payload 9,800
I	Translunar corr, lunar orbit insertion, plane change, deorbit, braking, hover and touchdown	11,013	LOX, LH_2	49,000	28,000	57,700
Landing gear fairing						1,500
Total weight						87,400



Payload Weight (lb)		
CM Structure, Heat Shield, Etc.		2291
CM Equipment		
Reaction control system	340	
Landing system	390	
Electrical system	310	
Environmental control	470	
Instruments and displays	245	
Furnishings and equipment	336	
Crew and suits	444	
Communications	105	
Instrumentation	252	
Scientific equipment	250	
Guidance and navigation	524	
Stabilization and control	74	
Radiation protection	466	
Total		4206
Service Module		
Electrical	1106	
Environmental control	353	
Communications	162	
Guidance and navigation	60	
Attitude control	700	
Total	2435	
Payload total	8932	
Growth provisions	868	
Design payload weight	9,800	

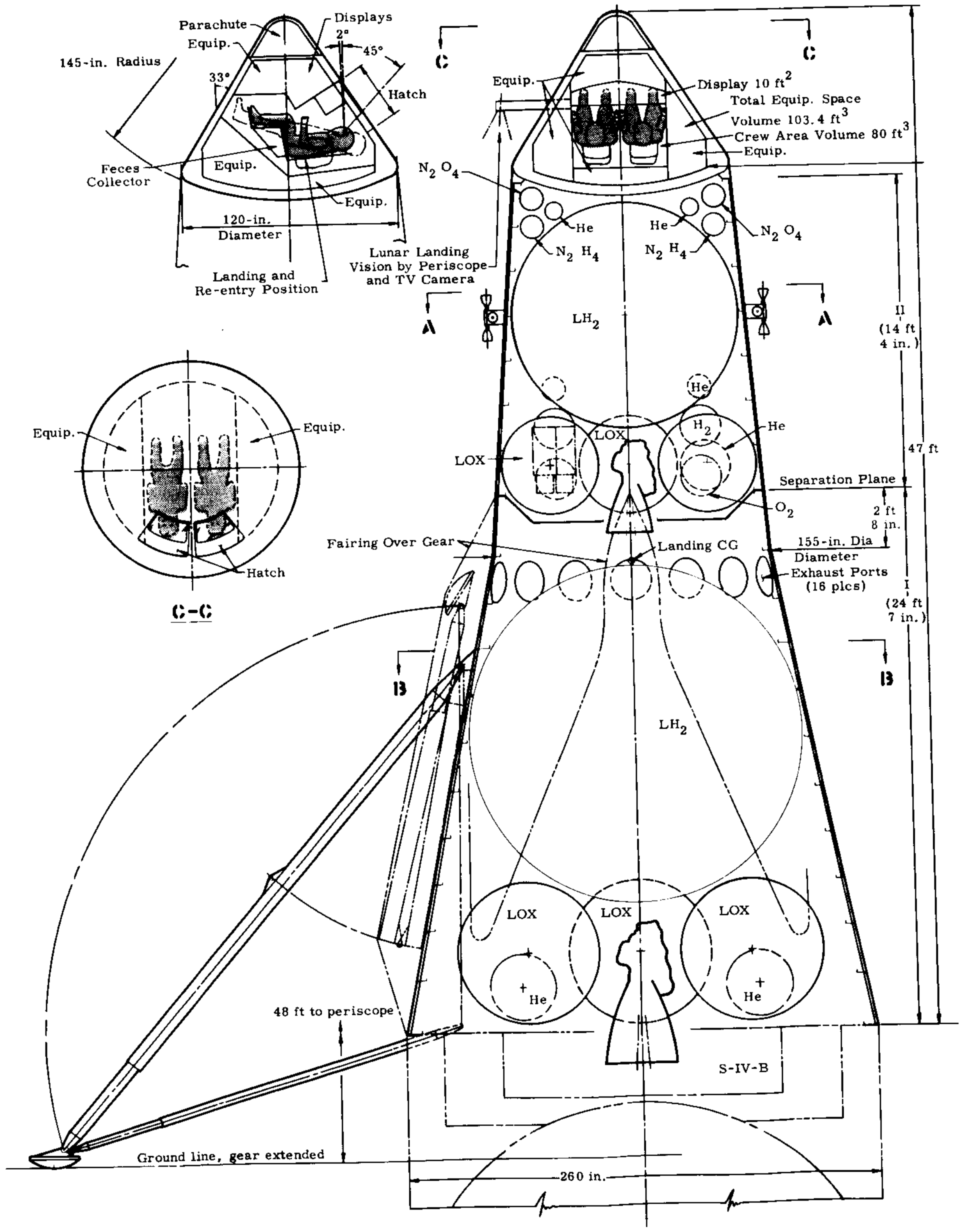
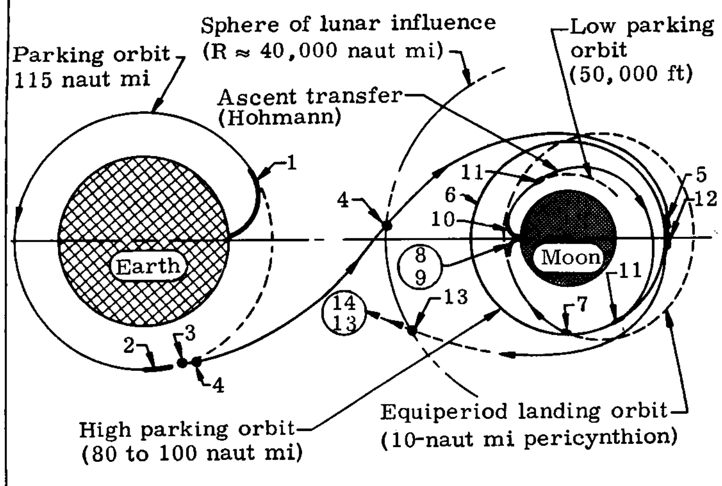


Fig. II-2. DF Configuration

[redacted]

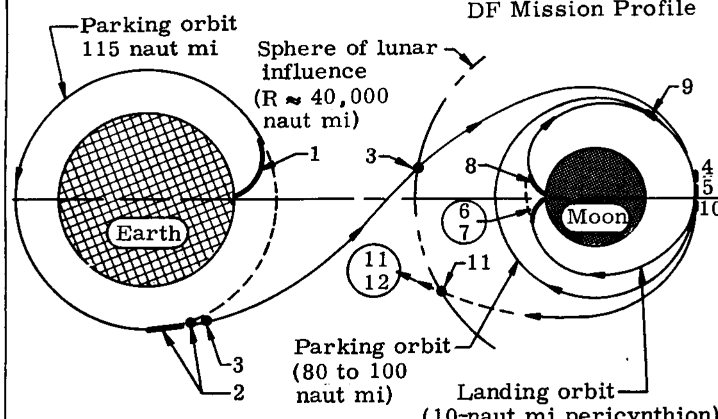
[redacted]

LOR Mission Profile



	Operation/Maneuver	Propulsion	ΔV (fps)
1.	Ascent to parking orbit	C-5	≈25,600
2.	Translunar insertion	C-5	≈10,800
3.	CM/SM repositioning (final C-5 separation)	SM-R	--
4.	Midcourse corrections, translunar (2)	SM-MΔ	330
5.	Lunar orbit insertion (incl plane change)	SM-MΔ	3,553
6.	CM and SM lunar coast (LEM separation from CM and SM)	LEM/T-R	--
7.	Landing orbit insertion	LEM/L-MΔ	410
8.	Braking to 1000-ft hover point	LEM/L-MΔ	6,560
9.	Hover-descent and land	LEM/L-MΔ	770
10.	Takeoff to low parking orbit (LEM/T separation from LEM/L)	LEM/T-MΔ	6,660
11.	Transfer, rendezvous and dock -- normal	LEM/T-R	220
	-- backup	SM-MΔ	524
	(LEM/T separation from CM and SM)		
12.	Transearth insertion	SM-MΔ	4,059
13.	Midcourse corrections, transearth (2)	SM-MΔ	330
14.	Earth reentry and landing (CM separation from SM)	CM-R	--

DF Mission Profile



	Operation/Maneuver	Propulsion	ΔV (fps)
1.	Ascent to parking orbit	C-5	≈25,600
2.	Translunar insertion (final C-5 separation)	C-5	≈10,800
3.	Midcourse corrections, translunar (2)	LLM-MΔ	330
4.	Lunar orbit insertion (incl plane change)	LLM-MΔ	3,553
5.	Landing orbit insertion	LLM-MΔ	150
6.	Braking to 1000-ft hover point	LLM-MΔ	6,210
7.	Hover-descent and land	LLM-MΔ	770
8.	Takeoff to parking orbit (CM & SM separation from LLM)	SM-MΔ	6,310
9.	Parking orbit insertion	SM-MΔ	220
10.	Transearth insertion (incl plane change)	SM-MΔ	3,553
11.	Midcourse corrections, transearth (2)	SM-MΔ	330
12.	Earth reentry and landing (CM separation from SM)	CM-R	--

C-5	----------	Saturn Launch Vehicle (S-IB, S-II and S-IVB)
CM	----------	Command Module
SM	----------	Service Module
LEM/L	----------	Lunar Excursion Module, Lander
LEM/T	----------	Lunar Excursion Module, Takeoff
LLM	----------	Lunar Landing Module
-M	----------	Main Propulsion
-R	----------	Reaction Control Propulsion
LOR	----------	Lunar Orbit Rendezvous Technique, 3 man
DF	----------	Direct Flight Technique, 2 man
Δ	----------	Gimbaled engine provides pitch and yaw attitude during thrusting period.
O	----------	Occur at some point between sphere of lunar influence and landing.

Fig. II-3. LOR and DF Mission Profiles

[redacted]

III. SYSTEM ANALYSIS

This section presents a brief summary of the operational and systems analyses conducted to define mission functions and sequences.

In order to evaluate the capability of the crew to perform assigned tasks it is necessary that all functions, both man and machine, be identified for both the LOR and the DF missions. The functional analyses provide the following:

(1) Systematic development of mission profiles to the maneuver phase level.

(2) Chronological identification of all mission functions.

(3) Definition of operational requirements as a basis for system configuration definition.

(4) Definition of spacecraft subsystem functions by mission phases.

(5) A basis for development of the recommended man-machine relationship considering reliability, weight, volume and state-of-the-art limitations.

(6) Definition of manual functions as a basis for crew task analysis.

1. Mission Profiles

The profiles for both the LOR and DF missions were defined to the maneuver phase level and are based on the general profiles outlined in Fig. II-3. The mission profile for LOR was developed during the LEM/Apollo proposal effort and is consistent with the mission concepts and requirements of NASA's LEM RFP MSC-63-181P, dated 24 July 1962. The DF mission profile was developed using the same overall mission profile concepts of the LEM/Apollo, except for the obvious differences that no repositioning during translunar flight is required and that the lunar landing and the ascent to lunar orbit are made directly.

Previous studies of the Apollo mission (reflected, for example, in Martin's October 1961 Apollo proposal to NASA) considered five midcourse corrections during translunar flight and five during transearth flight. The OS reliability estimates for the present study were based on two midcourse corrections for each of these phases. In the current analysis, the higher number of corrections was used in determination of crew tasks and workloads. For consistency with the OS figures, however, the two-correction assumption was retained in estimating equipment and system reliability.

The mission profile for the LOR is divided into 67 maneuver phases and the DF is divided into 55 maneuver phases (see Figs. III-1 and III-2). In subdividing the profile, minimum phase increments were selected so that most of the major functions (≈ 75%) within the phase would require completion before the next phase. The degree of detail, however, was held to a moderate level consistent with the scope and intent of this study.

[redacted]

MISSION PHASE → / MANEUVER →	EARTH ASCENT: Start Engines	Stage S-1 Ascent	Stage S-1 Separation	LES Tower Separation	Stage S-2 Ascent	Stage S-2 Separation	Vehicle Coast	Earth Orbit Insertion	EARTH ORBIT	TRANSLUNAR FLIGHT	LUNAR ORBIT-CSM/LEM	LUNAR DESCENT-LEM	LUNAR ORBIT-CSM	LUNAR SURFACE-LEM	LUNAR ASCENT-LEM	LUNAR ORBIT-CSM/LEM	TRANSEARTH FLIGHT AND LANDING
OPERATIONAL FUNCTION																	
NAVIGATION																	
1. Determine pos, vel and accel ---earth ref																	
2. Determine pos, vel and accel ---stellar ref																	
3. Determine pos, vel and accel ---lunar ref	▲	▲	▲	▲	▲	▲	▲	▲									
4. Determine range and range rate for rendezvous																	
5. Determine spacecraft attitude																	
6. Determine time ref	CM																
GUIDANCE																	
7. Compute req'd course	IU/GRD/CM	CM	IU, CM	IU, CM	CM	IU, CM	IU, CM	CM									
8. Compute current course	IU/GRD/CM	CM	IU, CM	IU, CM	CM	IU, CM	IU, CM	CM									
9. Provide steering commands		IU			IU			IU									
10. Provide vel control commands																	
11. Provide time ref memory	IU/GRD/CM	CM	IU, CM	IU, CM	CM	IU, CM	IU, CM	CM									
12. Provide functional sequence commands	IU/GRD		IU	IU		IU	IU										
13. Provide pos, vel, accel and attitude ref memory	IU/GRD/CM	CM	IU, CM	IU, CM	CM	IU, CM	IU, CM	CM									
STABILIZATION AND CONTROL																	
14. Determine attitude error	▲		IU	IU		IU	IU, CM	CM									
15. Provide attitude control commands		IU	IU	IU	IU	IU	IU	IU									
16. Provide thrust vector control commands																	
PROPULSION																	
17. Provide velocity increments	S-1	S-1	S-1 (retro)	(See LES below)	S-2	S-2 (retro)		S-3									
18. Provide velocity correction																	
19. Provide thrust vector control		S-4			S-2			S-3									
REACTION CONTROL																	
20. Provide attitude control	▲	▲	▲	S-3	▲	▲	S-3	▲									
21. Provide translation																	
COMMUNICATIONS																	
22. Provide voice/data link ---CM to earth	CM	CM	CM	CM	CM	CM	CM	CM									
23. Provide voice/data link ---CM to CM crew	CM	CM	CM	CM	CM	CM	CM	CM									
24. Provide voice/data link ---CM to LEM																	
25. Provide voice/data link ---LEM to earth																	
26. Provide voice/data link ---LEM to LEM crew																	
27. Provide TV/data link ---CM to earth	CM	CM	CM	CM	CM	CM	CM	CM									
28. Provide TV/data link ---LEM to earth																	
29. Provide TV/data link ---LEM to external monitoring																	
30. Provide TV/data link ---CM/LEM to internal monitoring	CM	CM	CM	CM	CM	CM	CM	CM									
31. Provide TV/data link ---Lunar surface to earth																	
32. Provide tracking signals		IU	IU	IU	IU	IU	IU	IU									
INSTRUMENTATION																	
33. Provide operational instrumentation	CM, S-1	CM, S-1	CM, S-2	CM	CM, S-2	CM, S-3	S-3, AS	S-3, AS									
34. Provide scientific instrumentation																	
SEPARATION																	
35. Provide separation LES to CM				CM													
36. Provide separation CM to SM																	
37. Provide separation CM to L-2																	
38. Provide separation CSM to S-3 (S-IV B)	▲	▲			▲		▲	▲									
39. Provide separation LEM to S-3 (S-IV B)																	
40. Provide separation LEM-1 to LEM-2																	
41. Provide separation S-3 to S-2						S-3											
42. Provide separation S-2 to S-1			S-2														
ENVIRONMENTAL CONTROL																	
43. Provide cabin/suit atmosphere																	
44. Provide cabin/suit humidity control																	
45. Provide cabin/suit temperature control	CM	CM	CM	CM	CM	CM	CM	CM									
46. Provide cabin/suit noxious gas control																	
47. Provide cabin particulate removal																	
48. Provide equipment temperature control																	
DOCKING																	
49. Provide docking interface	▲	▲	▲	▲	▲	▲	▲	▲									
CREW EQUIPMENT																	
50. Provide acceleration protection		CM			CM			CM									
51. Provide station positions	CM	CM	CM	CM	CM	CM	CM	CM									
52. Provide sanitation																	
53. Provide food and water																	
54. Provide emergency equipment																	
55. Provide exercise equipment																	
56. Provide sleeping facilities																	
57. Provide garments	CM	CM	CM	CM	CM	CM	CM	CM									
58. Provide for decompressed operation																	
59. Provide for extra vehicular operations																	
60. Provide medical instrumentation	CM	CM	CM	CM	CM	CM	CM	CM									
ELECTRICAL POWER																	
61. Provide electrical power source	S1, S2, S3, SM, L2	S1, S2, S3, IU	S2	SM	S2, S3, IU, L2, SM	S3	S3, IU, L1, SM	S3, IU, L2, SM									
62. Distribute to systems	S1, S2, S3, SM, CM	S1, S2, S3, SM, CM, IU, L1, L2	S2	SM, CM	S2, S3, IU, L2, SM, CM	S3	S3, IU, L1, SM, CM	S3, IU, L2, SM, LM									
STRUCTURAL																	
63. Provide main and equipment supporting structure	ASV	ASV	ASV	ASV	ASV	ASV	ASV	ASV									
64. Provide pressurized crew compartment	CM	CM	CM	CM	CM	CM	CM	CM									
65. Provide ingress and egress	CM																
66. Provide meteoroid protection																	
67. Provide radiation protection																	
68. Provide thermal control		ASV	ASV	ASV	ASV	ASV	ASV	ASV									
69. Provide visibility	CM		CM	CM		CM	CM										
70. Provide crew transfer ---CM to LEM																	
71. Provide reentry thermal protection																	
LANDING																	
72. Deploy landing system																	
73. Provide soft lunar landing	▲	▲	▲	▲	▲	▲	▲	▲									
74. Provide soft earth landing																	
75. Provide landing aids																	
76. Provide recovery aids																	
LAUNCH ESCAPE																	
77. Provide launch pad escape	LES		▲		▲	▲	▲	▲									
78. Provide Stage I ascent escape		LES															
79. Provide LES tower jettison				LES													
DISPLAYS AND CONTROLS																	
80. Provide crew displays	CM	CM	CM	CM	CM	CM	CM	CM									
81. Provide crew controls (to be determined)	CM																

DATA FOR THESE MISSION PHASES WAS ALSO DETERMINED BUT WAS NOT INCORPORATED BECAUSE OF SPACE LIMITATION

Key to Field Symbols

S-1	Stage 1, S/C, C-5
S-2	Stage 2, S II, C-5
S-3	Stage 3, S IV B
IU	Instrument Unit, Saturn
L-1	LEM Lander Stage
L-2	LEM Takeoff Stage
LEM	Combined L1 and L2
SM	Service Module
CM	Command Module
CSM	Combined CM and SM
LES	Launch Escape System (tower)
AS	Apollo Spacecraft

LAUNCH VEHICLE (LV)
APOLLO SPACECRAFT (AS)
APOLLO SPACE VEHICLE (ASV)

▲ No Function This Maneuver

(81 functions)
(67 maneuvers)
5427 Function/Phase Maneuvers Analyzed

Fig. III-1. Primary Functional Analysis, LOR

[redacted]

[redacted]

MISSION PHASE →	EARTH ASCENT								EARTH ORBIT	TRANSLUNAR FLIGHT	LUNAR ORBIT-INITIAL	LUNAR DESCENT	LUNAR SURFACE	LUNAR ASCENT	LUNAR ORBIT-RETURN	TRANSEARTH FLIGHT
MANEUVER →	Start Engines	Stage S-1 Ascent	Stage S-1 Separation	LES Tower Separation	Stage S-2 Ascent	Stage S-2 Separation	Prepare for Insertion	Earth Orbit Insertion S-3								
OPERATIONAL FUNCTION																
NAVIGATION 1. Determine pos, vel and accel--earth ref 2. Determine pos, vel and accel--stellar ref 3. Determine pos, vel and accel--lunar ref 5. Determine spacecraft attitude 6. Determine time ref	▲	▲	▲	▲	▲	▲	▲	▲								
GUIDANCE 7. Compute required course 8. Compute current course 9. Provide steering commands 10. Provide vel control commands 11. Provide time ref memory 12. Provide functional sequence commands 13. Provide pos, vel, accel and attitude ref memory	IU/GRD/CM IU/GRD/CM IU/GRD/CM IU/ GRD IU, CM/GRD	CM CM IU CM IU, CM	IU, CM IU, CM IU, CM IU IU, CM	IU, CM IU, CM IU, CM IU IU, CM	CM CM IU CM IU, CM	IU, CM IU, CM IU, CM IU IU, CM	IU, CM IU, CM IU, CM IU IU, CM	CM CM IU CM IU, CM								
STABILIZATION AND CONTROL 14. Determine attitude error 15. Provide attitude control commands 16. Provide thrust vector control commands	▲	IU	IU IU	IU IU	IU	IU IU	IC, CM IU	CM IU								
PROPULSION 17. Provide velocity increments 18. Provide velocity correction 19. Provide thrust vector control	S-1	S-1 S-1	S-1 (retro)	(See LES below)	S-2 S-2	S-2 (retro)	▲	S-3 S-3								
REACTION CONTROL 20. Provide attitude control	▲	▲	▲	S-3	▲	▲	S-3	▲								
COMMUNICATIONS 22. Provide voice/data link--CM to earth 23. Provide voice/data link--CM to CM crew 27. Provide TV/data link--CM to earth 29. Provide TV/data link--CM to external monitoring 30. Provide TV/data link--CM to internal monitoring 31. Provide TV/data link--lunar surface to earth 32. Provide tracking signals	CM CM CM	CM CM CM IU	CM CM CM IU	CM CM CM IU	CM CM CM IU	CM CM CM IU	CM CM CM CM IU	CM CM CM IU								
INSTRUMENTATION 33. Provide operational instrumentation 34. Provide scientific instrumentation	CM, S-1	CM, S-1	CM, S-2	CM	CM, S-2	CM, S-3	CM	CM, S-								
SEPARATION 35. Provide separation LES to CM 36. Provide separation CM to SM 37. Provide separation SM to LLM 38. Provide separation LLM to S-3 (S-IVB) 40. Provide separation S-3 to S-2 41. Provide separation S-2 to S-1	▲	▲	S-2	CM	▲	S-3	▲	▲								
ENVIRONMENTAL CONTROL 42. Provide cabin/suit atmosphere 43. Provide cabin/suit humidity control 44. Provide cabin/suit temperature control 45. Provide cabin/suit noxious gas control 46. Provide cabin particulate removal 47. Provide equipment temperature control	CM	CM	CM	CM	CM	CM	CM	CM								
CREW EQUIPMENT 49. Provide acceleration protection 50. Provide station positions 51. Provide sanitation 52. Provide food and water 53. Provide emergency equipment 54. Provide exercise equipment 55. Provide sleeping facilities 56. Provide garments 57. Provide for decompressed operation 58. Provide for extra vehicular operations 59. Provide medical instrumentation	CM CM CM	CM CM CM CM	CM CM CM	CM CM CM	CM CM CM CM	CM CM CM	CM CM CM	CM CM CM CM								
ELECTRICAL POWER 60. Provide electrical power source 61. Distribute to systems	S1, S2, S3, SM, S1, S2, S3, SM, CM	S1, S2, S3, SM IU S1, S2, S3, SM IU	S2 S2	SM SM, CM	S2, S3, IU, SM S2, S3, IU	S3 S3	S3, IU, SM S3, IU, AS	S3, IU S3, IU								
STRUCTURAL 62. Provide main and equipment supporting structure 63. Provide pressurized crew compartment 64. Provide ingress and egress 65. Provide meteoroid protection 66. Provide radiation protection 67. Provide thermal control 68. Provide visibility 70. Provide reentry thermal protection	ASV CM CM CM	ASV CM ASV	ASV CM ASV CM	ASV CM ASV CM	ASV CM ASV	ASV CM ASV CM	ASV CM ASV	ASV CM ASV								
LANDING 71. Deploy landing system 72. Provide soft lunar landing 73. Provide soft earth landing 74. Provide landing aids 75. Provide recovery aids	▲	▲	▲	▲	▲	▲	▲	▲								
LAUNCH ESCAPE 76. Provide launch pad escape 77. Provide Stage I ascent escape 78. Provide LES tower jettison	LES	LES	▲	LES	▲	▲	▲	▲								
DISPLAYS AND CONTROLS 79. Provide crew displays 80. Provide crew controls (to be determined)	CM CM	CM	CM	CM	CM	CM	CM	CM								

DATA FOR THESE MISSION PHASES WAS ALSO DETERMINED BUT IS NOT INCORPORATED BECAUSE OF SPACE LIMITATION.

Key to Field Symbols

S-1	Stage 1, S/C, C-5
S-2	Stage 2, S II, C-5
S-3	Stage 3, S IV B
IU	Instrument Unit, Saturn
LLM	Lunar Landing Module
SM	Service Module
CM	Command Module
CSM	Combined CM and SM
LES	Launch Escape System (tower)
AS	Apollo Spacecraft
▲	No Function This Maneuver
GRD	Ground Launch Support

LAUNCH VEHICLE (LV) · APOLLO SPACECRAFT (AS) · APOLLO SPACE VEHICLE (ASV)

LAUNCH VEHICLE (LV)
(71 functions) (55 maneuvers)
(3905 function/phase maneuvers analyzed)

Fig. III-2. Primary Functional Analysis, DF

[redacted]

2. Primary Functional Analysis

Figures III-1 and III-2 represent the primary functional analyses conducted in accordance with the mission concepts to identify all major functions occurring during the normal LOR and DF missions, whether performed by man or machine. These analyses provide a qualitative basis for determining operational and functional requirements for the subsequent configuration development of the spacecrafts and their subsystems.

The primary functional analysis for LOR is essentially that conducted during Martin's LEM proposal effort, modified for consistency with the present study ground rules. This analysis included the systematic identification of 81 categories of significant normal functions for 67 phases of the mission profile; i.e., a matrix of 5427 function/phases were analyzed. Functions occurring within each phase were identified with respect to the appropriate spacecraft module.

The primary functional analysis for DF was developed on a conceptually equivalent basis with the LOR, allowing for the fundamental differences between the two missions. This analysis included the systematic identification of 71 categories of significant normal functions for 55 phases of the mission profile; i.e., a matrix of 3905 function/phases was analyzed and identified with respect to a specific spacecraft module.

Using the primary functional analysis for DF, the operational requirements by major system categories were defined. The scaled-down two-man system was reviewed to assure that the subsystems possessed the required functional capability considering size and weight limitations. A brief comparative review was also made of the LOR configuration for consistency between the updated LOR primary functional analysis and the operational capability of the proposed LEM/Apollo configuration.

3. System Functional Analysis

Subsequent to the development of primary configurations and system design, the DF and LOR were analyzed to the subsystem and major component levels to assure compatibility with the operational/functional requirement. These analyses serve to: (1) evaluate system configuration and design, (2) define automatic versus manual relationship, (3) identify crew functions to provide a basis for defining man-machine interface and (4) provide a basis for performing an analysis of crew tasks.

Preliminary studies indicated that, from the reliability standpoint alone, a redundant automatic system with manual backup for decisions, sequencing, switching and control would normally be preferred. Initially, the system was so visualized. Automatic functions were then reviewed to determine those which could be performed manually with high reliability such that, considering state-of-the-art limitations, a weight/reliability tradeoff would favor the manual approach. The preliminary systems configurations were then revised to reflect the recommended incorporation of man in the loop. One significant factor in the assignment and analysis of manual functions is that the nature and importance of certain tasks, and the available time and information for verification and correction, are such that manual operations can be designated as repetitive. Where clearly justified, this "manual redundancy" was incorporated in the reliability models.

Figures III-3 and III-4 summarize the system functional analysis of the LOR and DF systems configurations, respectively. These figures list the major subsystems and/or major components for the two configurations. The functions determined dur-

System	Equipment	Function*	Earth Ascent (Start Engines, S-1 Ascent, S-1 Sep, LES Sep, S-2 Ascent, S-2 Sep, Coast, EO Inser)	Earth Orbit (Orbit Verif, Coast, Preparation, TL Inser)	Translunar Flight (Preparation, Reposition CSM, Preparation, S-3 Sep, Preparation, 1st Course Correc, Course Verif, Coast, Preparation, Final Course Correc, Preparation, LO Inser)	Lunar Orbit CSM/LEM (Orbit Verif, L Site Survey, Crew Transfer, Preparation, LEM Sep)	Lunar Descent LEM (Land Orbit Inser, LO Verif, Preparation, Braking, Hover-Descent, Touchdown)	Lunar Orbit CSM (MON LEM Landing, Supt LEM Oper, Supt LEM Rendz)	Lunar Surface LEM (S/C Verif, Secure S/C, Site Verif, Surface Oper, Preparation Takeoff)	Lunar Ascent LEM (Ascent to Lunar Orbit, Coast and Preparation, Orbit Transfer, Coast and Preparation, Rendezvous, Docking)	Lunar Orbit CSM/LEM (Secure LEM, Crew Transfer, Preparation, LEM Sep, Preparation, Trans-E Inser)	Transearth Flight (Preparation, 1st Course Correc, Verif, Coast, Preparation, Final Course Correc, Verif, SM Sep, Preparation, Atmos Re-entry, Descent, Touchdown)	Oper Mode
I. COMMAND MODULE													
A. Nav and Guid	1. IMU 2. OMU (and space sextant) 3. Computer 4. Control and display unit 5. Electronics assembly	11, 12 1, 2, 3, 5 7, 8, 9, 12	All All--A	All X X X C C C A	All X X X X X X C A A A C A C C C A C A	All X X C C A A A		All All C C C			All X A A A A C A	All X X X X X X X X C A C C C A C A C A C C All phases All phases	A M - A A
B. Stab and Cont	1. Autopilot-electronics 2. Rate gyro package 3. Attitude ref--SS* 4. Power supply unit	15, 16 13 14	All--A	C (E) (E) A All	(E) M (E) A (E) A (E) C (E) A (E) A X X X X All	(E) C A A A All		A C A All			A A A A (E) A X All	(E) A (E) C (E) A (E) A (E) A A A X X X All All	A A A
C. React Cont	1. Thrust units 2. Prop. supply and press--SS	20										(E) A A A A A (E) A A A A A	
D. Elect. Pwr	1. Batteries--A_g - Z_n 2. Dist and cont--SS	61 62										E A A	
E. Environ Cont	1. Suit/cabin air supply--SS 2. Air regen--SS 3. H_2O supply--SS 4. Water evaporator 5. Liquid coolant--SS 6. Equipment cooling--SS 7. Prelaunch cooling--SS 8. O_2 supply--SS	43, 58 43, 44, 45, 46, 47, 48 45 45 45, 48 48 45, 48 43, 48	X X X X X X X	All		All		All			All	All phases All phases All phases X X All phases All phases All phases (E) A A A A A	A A A A A
F. Launch Escp	1. Escape rocket 2. Thrust vect cont--SS 3. Jettison rocket	77, 78 19 78	X X X X X X X X X X X X										A A A
G. Communications	1. VHF--SS 2. VHF, near field--SS 3. HF--SS 4. C-band beacon 5. HF/VHF beacon 6. Earth tracking--SS 7. CM intercom--SS 8. Closed circuit TV--SS	6, 22, 27 23 22, 75 32 32, 75 23 27, 29, 30	All--A All--A	All--A All--A	A A A A A A E A A A A A A E C A A A A A	E A A C A		A A A C C C			A A E C	E A A A A A E A A A A A E A C A A A A A All phases All phases	C C
H. Oper Instrm	1. Digital clock 2. PCM--SS 3. PAM/FM--SS 4. FM/FM--SS 5. Tape recorder-crew 6. Tape recorder-instrument 7. Photo cameras 8. TV cameras 9. Telescope 10. Display and controls	11, 33 33 33, 51 33 33 33 33 30, 33 33 12, 79, 80	All--A X X X X X X X X	All--A X X	All--M X X X X X X	All--M		All--M			All--A X X	All phases M M M M M M M M A A A A X X X All phases All phases X X X All phases All phases All phases All phases	A E A M E M A M M
I. Crew Equip.	1. Seats 2. Restraint 3. Couch 4. Suits and garments 5. Sanitation--SS 6. Food and water--SS 7. Emergency equipment 8. Rec and exer equip. 9. Port life support--SS	50, 51 50 56 57, 58 52 53 54 55 58, 59	X X X X X X X	X X X	X X X X X X X X X X X X X X X X X X	X X X X X X X X		X X X X X			X X X X	All phases X X X X X X X X All phases X X X X X X X X X X X X X X X All phases X X	M M M M M M M M M
J. Earth Lndg	1. Chutes and deploy--SS 2. Sequence unit	74 12, 72										X (E) A	A
K. Structural	1. Structure 2. Heat shield 3. Hatches & air lock 4. Windows 5. Press cabin 6. Impact attenuation--SS	63, 66, 67, 68 71 65 69 64 74	X X X X	X	X X X	X X X X					X X X X	All phases X X X X X X All phases X	A A M A A C
L. Separation	1. LES sep--SS 2. SM sep--SS	35 36	X									X	A C
II. SERVICE MODULE													
A. React Cont	1. Thrust units 2. Prop supply & press--SS	20		All All	All All	All All		All			All All	X X X X X X X X X X X X X X X X	A A
B. Propulsion	1. Engine 2. Gimbaling--SS 3. Prop supply & press--SS 4. Prop util--SS	17, 18 19 -- --			(E) A A A X X X (E) A A A X X X						A X A X	A A X X A A X X	- A - A
C. Separation	1. SM/S-3 sep--SS	38			X								(E)
D. Environ cont	1. O_2 & N_2 supply--SS 2. Space radiators 3. Liq coolant circuit 4. Equip cool--SS	43 45, 48 45, 48 48										All phases All phases All phases All phases	A A A A
E. Elect. Pwr	1. Fuel cell batt--SS 2. Fuel supply--SS 3. Heat exchangers 4. Liq cool circuit 5. Space radiators 6. Dist & cont--SS											All phases All phases All phases All phases All phases All phases	
F. Comm	1. DSIF--SS 2. X-band alt radar--SS	4			E A A A A A A E	A--All A A A A		A--All A--All			A--All A--All	A A A E E	- -
G. Oper Instrm	1. Meteorite detec--SS 2. Radiation detec--SS 3. Mag storm detec--SS 4. Abrasion detec--SS 5. Solar flare detec--SS 6. S/C sys sensors--SS											All phases All phases All phases All phases All phases All phases	A A A A A A
H. Structural	1. Structure											All phases	A
III. LEM-TAKEOFF													
A. Nav & Guid	1. IMU 2. OMU 3. CMPTR 4. Cont & disp unit 5. Electr assy	5 1, 2, 3, 4 6, 7, 8				X X X C E A X X	All X A C C A M M A--All All		X X X X C C A E X X	All X X X C C C A--All All			A M - - A
B. Stabe & Cont	1. Autopilot-electr 2. Rate gyro package 3. Attitude ref--SS 4. Power supply unit					(E) A A A A A A A	A C (E) A M M All All All		(E) A X X X X	A A (E) M M All All All			- A A A
C. Propulsion	1. Engine 2. Gimbaling--SS 3. Prop supply & press--SS								(E) A X (E) A				- A -
D. React Cont	1. Thrust units 2. Prop supply & press--SS								(E) (E)	A--All A--All			-
E. Elect Pwr	1. Batteries-Ag Zn 2. Dist & cont--SS								(E) X	A-All All	A A A A X X X X		- A
F. Environ Cont	1. Suit/cabin air supply--SS 2. Air regen--SS 3. H_2O supply--SS 4. Water evaporator 5. Liquid cool--SS 6. Equip't cool--SS 7. Prelaunch cool--SS		X			(E) A X X X X X X X X X X	A--All All All All All All		A--All All All All All All	A--All All All All All All	X X X X X X X X X X X X		A
G. Comm	1. VHF--SS 2. DSIF--SS 3. X-band LD & rndz radar 4. Intercomm--SS 5. Closed circuit TV--SS					E A E A E A E A E C	A--All A--All A--All A--All C--All		A--All A--All E A--All C--All	A--All A--All A--All A--All C--All	A A A C		- - - - -
H. Oper Instrm	1. PCM--SS 2. Digital clock 3. Tape recorder 4. Photo cameras 5. TV cameras (internal) 6. Telescope 7. Disp & cont--SS	5				E A E A X X X X X X X X X X	A--All A--All All All All All All		A--All A--All All All All All All	A--All A--All All All All All All	A A X X X X X		- - M C A M M
I. Crew Equip	1. Seats 2. Restraint--SS 3. Space suits 4. Port life supt--SS 5. Food, water & sanitation--SS 6. Emerg equip't					X X X X X X X	All X X X X X All		All X All X X X X All	All X X X All X All	X X X X X		M M M M M M
J. Separation	1. LEM/L sep--SS								X				(E)
K. Structural	1. Structure 2. Hatches 3. ~~Windows~~ 4. Press cabin					X X X X X X X X	All X X X All		All X X X X X All	All X X X All	X X X X X X X X X		A M A A
IV. LEM-LANDER													
A. Propulsion	1. Engine 2. Gimbaling--SS 3. Prop supply & press--SS					(E) X (E)	A A A X X X A A A						- A -
B. Elect. Pwr	1. Fuel cell batt--SS 2. Fuel supply--SS 3. Dist & cont--SS					X X X X (E)	All All A--All		All All A--All				A A -
C. Environ Cont	1. H_2O supply--SS 2. O_2 supply--SS 3. Liquid heat--SS					X X X X X X	All All All		All All All				A A A
D. Communication	1. Vel & alt radar--SS 2. Port TV/VHF trans--SS					(E) A	A--All		C A				- -
E. Oper Instrm	1. TV camera-external						X X X		X X X				M
F. Scientific equip	1. Lunar atmos anal 2. Graviometer 3. Magnetometer 4. Rad spectrometer 5. Spec return container 6. Rock & soil anal 7. Seismographic equip 8. Soil temp instrm								X X X X X X X X				M M M M M M M M
G. Lunar Touchdown	1. Strut deploy--SS 2. Landing struts 3. Emerg energy abs 4. Landing aids					X	M X X		A--All				(E) - A M
H. Structural	1. Structure 2. Access doors 3. Exhaust ports					X X X X	All		All X X X	X			A M A
I. Separation	1. LEM/S-3 separation--SS				X								(E)

NOTES:

X Denotes see R. H. column for mode of operation.
A Denotes auto operation.
M Denotes manual operation.
C Denotes combination of auto & manual operation.
E Denotes manual enabling of auto operation.
All Denotes same for all of that phase.
(E) Denotes auto enabling with manual back-up.
EO--Earth orbit
TL--Translunar
LO--Lunar orbit
LD--Lunar Descent
TE--Transearth

Fig. III-3. System Functional Analysis, LOR

[redacted]

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SYSTEM	EQUIPMENT	MANEUVER FUNCTION	Earth Ascent (Start Engines, S-1 Ascent, S-1 Sep, LES TWR Sep, S-2 Ascent, S-2 Sep, Preparation, EO Inser S-3)	Earth Orbit (Orbit Verif, Coast, Preparation, TL Inser S-3)	Translunar Flight (Preparation, S-3 Sep, Preparation, 1st Course Correc, Course Verif, Coast, Preparation, Final Course Correc, Preparation, LO Inser)	Lunar Orbit (LO Verif, Site Survey, Preparation, LO Inser)	Lunar Descent (LO Verif, Preparation, Braking, Hoover--Descent, Touchdown)	Lunar Surface (S/C Verif, Secure S/C, Site Verif, Surface Mission, Preparation Takeoff)	Lunar Ascent (Ascent, Ascent Verif, Preparation, LO Inser)	Lunar Orbit (LO Verif, Preparation, TL Inser)	Transearth Flight (Preparation, 1st Course Corr, Course Verif, Coast, Preparation, Final Course Corr, Course Verif, SM Sep, Preparation, Atmos re-entry, Descent, Touchdown)	Oper Mode
I. COMMAND MODULE												
A. Nav and Guid	1. IMU 2. OMU and space sextant 3. Computer 4. Control and display unit 5. Electronics assembly	11, 13 1, 2, 3, 5 7, 8, 9, 12 -- --	All All--A All All	All X X X C C C A All All	All X X X X X C A C A C C C A C A All	All X X X C C C A All All	All X X C C A M M All All	X X X X C C X X	All X X A C C A All All	All X X C C A All All	All X X X X X X X C A C C C A C A C A C C All All	A M - A A
B. Stabil and Cont	1. Autopilot--electronics 2. Rate gyro package 3. Attitude reference system 4. Power supply unit	15, 16 13 14 N&G and S&C power	All--A All	C E E A All All	E A E A C C E A E A X X X All All	E C E A X All All	E E A M M X X X All All	E X A X X	A E E A X X All All	E E A X All All	E A E C E A E A E A M M X X X X All All	- A A A
C. React. Cont	1. Thrust units 2. Prop. supply and press.--SS*	20 --									E A A A A E A A A A	- -
D. Electr Power	1. Batteries, silver-zinc 2. Dist and cont--SS	60 61									X X X X X E A A A A A	A -
E. Environ Cont	1. Suit/cabin air supply--SS 2. Air regen--SS 3. O_2 supply 4. H_2O supply--SS 5. Liquid coolant--SS 6. Water evaporator 7. Equip. cool.--SS 8. Prelaun cool.--SS	42, 57 42, 43, 44, 45, 46, 47 42, 57 44 44, 47 44 47 44, 47	X X X X X X X X	All	All phases All phases All phases All phases All phases	All	All	All	All	All	E A A A A A X X	A - A A A A A A
F. Launch Escape	1. Escape rocket 2. Thrust vect cont--SS 3. Jettison rocket	76, 77 19 78	X X X X X X X X X X X X									A A A
G. Communication	1. VHF--SS 2. VHF near field--SS 3. HF--SS 4. C-band beacon 5. HF/VHF beacon 6. Earth tracking--SS 7. Intercom--SS 8. Closed circuit TV--SS 9. Portable TV/trans--SS	6, 22, 27 23, external crew 22, 75 32, near earth 32, 75 -- 23 27, 29, 30 31	All--A All--A	All--A All--A	A A A A E A A A A E C A A A A A All phases All phases	C A	C A A A	X A A A A A E A	A A A A	A	E A A A A A E A E A A A A A E A C A A A A A A	- E - - - C C -
H. Oper Instrum	1. Digital clock 2. PCM--SS 3. PAM/FM--SS 4. FM/FM--SS 5. Tape recorder 6. Tape recorder 7. Photo cameras 8. TV cameras--internal 9. Telescope 10. Displays and controls	11, 33, prim. time ref 33, prim. telem 33, 51, sec telem 33, crew telem 33, crew use 33, instrum and backup 33 30, 33 33 12, 79, 80	All--A X X X X X X X X	All--A X X	All phases All--E X X X All phases All phases X X X All phases All phases All phases All phases	All--A X X	All--A X X X X X X	All--A	All-A X X X X	All-A X X	E E E E E E E E A A A A X X X X X X	A - E A M E C (selective use) A M (selective use) M
I. Crew Equip.	1. Seats 2. Restraint--SS 3. Couch 4. Space suits and garments 5. Sanitation--SS 6. Food and water--SS 7. Emergency equip. 8. Rec and exercise equip. 9. Portable life support--SS	49, 50 49 55 (sleeping) 56, 57 51 52 53 54 57, 58	X X X X X X X	X X X	All phases X X X X All phases X X X X X X X X X X All phases X X	X X X X X X X	X X X X X	X X X X X X X X X X	X X X X	X X X	X X X X X X X X X X X X X X X X X X X X	M M M M M M M M M
J. Earth Landing	1. Parachutes and deploy--SS 2. Sequence unit	73 12, 71									E A	
K. Structural	1. Structure 2. Heat shield 3. Hatches and air-lock 4. Windows 5. Pressure cabin 6. Impact attenuation	62, 65, 66, 67 70 64 68 63 73 (earth landing)	X X X X	X	All phases X X All phases	X	X X X	X X X X X		X	X X X X X X	A A M A A C
L. Separation	1. LES separation--SS 2. SM separation--SS	35 36	X								X	A E
II. SERVICE MODULE												
A. React Cont	1. Thrust units 2. Prop supply and press--SS*	20-EO and all except re-entry --		All All	All All	All All	All All		All All	All All	All All	A A
B. Propulsion	1. Engine--SS 2. Gimbaling--SS 3. Prop, supply and press--SS 4. Prop utilization--SS	17, 18 19 -- --						E E	A A X X A A A A	A X A A	A A X X A A A A	- - - -
C. Environ Cont	1. O_2 and N_2 supply--SS 2. Space radiators 3. Liq coolant circuit 4. Equip cool--SS	42 44, 47 44, 47 47			All phases All phases All phases All phases							A A A A
D. Electr Pwr	1. Fuel cell batt--SS 2. Fuel supply--SS 3. Heat exchangers 4. Liquid cool circuit 5. Space radiators 6. Disp and cont--SS	60 -- Water separation -- -- 61			All phases All phases All phases All phases All phases All phases							A A A A A A
E. Comm	1. DSIF comm--SS 2. X-band alt radar--SS	22 3			E A A A A A A	A-All E A A A	A-All A A A A E	A-All E	A-All A A A A	A-All A A E	A A A A	-- --
F. Oper Instrum	1. TV camera, external 2. Meteorite detec--SS 3. Radiation detec--SS 4. Mag strom detec--SS 5. Abrasive detec--SS 6. Solar flare detec--SS 7. S/C sys sensors--SS	29 33, 65 33, 66 33 33 33, 66 33	X X X	X	X X X All phases All phases All phases All phases All phases All phases	X	X X X	X X X		X	X	M A A A A A A
G. Separation	1. LLM sep--SS 2. CM sep interface	37 36							X		X	A A
H. Structural	1. Structure 2. Access doors	52, 65, 66, 67 64			All phases			X X				A M
III. LUN LAND MODULE												
A. Propulsion	1. Engine(s)--SS 2. Gimbaling--SS 3. Prop supply and press--SS 4. Prop util--SS	17, 18 19 -- --			E A A A X X X E A A A X X X	A X A X	A A X X A A X X					- A - A
B. Environ Control	1. Water supply--SS 2. Water press--SS	Storage --						X X X X X X X X X X				M M
C. Lun Touchdown	1. Strut deploy--SS 2. Lndg struts 3. Emerg energy abs 4. Lndg aids	71 72 72 74				X	X X X	X X X X X				M A A M
D. Separation	1. LV sep--SS 2. SM sep interface	38 37			X			X				M A
E. Scientific Instrum	1. Lun atmos anal 2. Gravimeter 3. Magnetometer 4. Rad spectrometer 5. Spec return container 6. Rock and soil anal 7. Seismographic equip 8. Soil temp instrument	34 34 34 34 34 34 34 34						X X X X X X X X	NOTES: X Denotes see RH column for mode of operation A Denotes automatic operation M Denotes manual operation C Denotes combination operation (usually enabling an auto. oper.)			M M M M M M M M
F. Structural	1. Structure 2. Access doors 3. Exhaust ports	62, 65, 66, 67 64 37			All phases			X X X				A M A

*SS = subsystem

Fig. III-4. System Functional Analysis, DF ing the primary functional analysis are referenced in the "function" column adjacent to the corresponding items. Equipment usage and normal mode of operation are indicated with respect to the maneuver/operation phase. The normal mode of operation is indicated as E, A, M or C, where E denotes manual enabling of a mode, A denotes automatic operation, M denotes primarily manual operation and C denotes a combination of manual and automatic operation.

4. Man-Machine Interface

The definition of the man-machine interface is presented in Figs. III-5 and III-6 for the LOR and DF respectively. The purpose of this definition is to summarize, in a form consistent with the basic equipment reliability tables, the areas and the manner in which the crew affects system performance. The summary indicates whether man is redundant to the automatic systems or is a critical man in the loop and whether his function permits verification and corrective action.

The interface definitions are based on the corresponding system functional analysis and provide a basis for quantitatively incorporating the crew performance assessment into the system reliability mathematical models. The four categories of crew involvement considered are defined as follows:

(1) Manual backup to automatic system--for sequencing, switching, decision-making and general systems management functions.

(2) Primary man-in-the-loop function--assigned as manual because of weight advantages or state-of-the-art limitations.

(3) Primary manual function with verification/correction capability.

(4) Manual enabling of a mode of operation.

Functions which are to be treated in the reliability mathematical models as not critical to mission success are so indicated in Figs. III-5 and III-6.

A. EMERGENCIES AND ABORTS

The general LOR and DF operations discussed thus far have been restricted to "nominal" missions, with no failures or emergencies considered. A complete analysis of all possible emergencies was not feasible within the scope of this study. In order to gain some insight into the effects of crew performance during "off-design" situations, the abort profiles for both LOR and DF were reviewed; seven emergency situations were selected to be analyzed for the LOR mode and six for the DF. The situations examined were noncatastrophic emergencies involving several subsystems. They were selected as having realistic possibility of occurrence and similar initial conditions for both modes and only emergencies amenable to analysis and evaluation were chosen. As in the nominal missions analyses, the functional steps and man-machine relationship were determined for each emergency case. Crew tasks were then analyzed and crew performance evaluated.

1. Abort Maneuver Profiles

The nominal abort maneuver profiles for both the LOR and DF methods are summarized in Table III-1. This figure outlines the maneuver sequence required for

LOR Man-Machine Performance Interface by Mission Steps

Spacecraft Systems and Mission Steps	1st Stage	2nd Stage	Earth Orbit Coast	3rd Stage (2 Burns)	LEM Transfer	Midcourse (2 Correc)	Trans-Lunar Coast	Lunar Orbit Retro	Lunar Orbit Coast	CM Orbit Coast	LEM Only: LEM Separation	LEM Only: Descent to Moon	LEM Only: Landing On Moon	LEM Only: Lunar Operations	LEM Only: Lunar Launch	Lunar Rendez & Dock	Lunar Orbit Escape	Midcourse (2 Correc)	Trans-Earth Coast	Earth Entry and Landing
A. CM and SM																				
Nav (OMU & comput's)	—	—	▲	—	—	—	▲	—	▲	▲						▲	—	—	▲	▲
Guid (steering cmds)	—	—	—	◪	—	◪◪*	—	◪	—	—						—	◪	◪◪*	—	—
Stab & cont	—	—	◪*	◪	▲	◪◪	◪*	◪	◪	◪*						◪	◪	◪◪	◪*	◪
React cont	—	—	—	—	—	—	—	—	—	—						—	—	—	◪	
Elect pwr	—	—	—	—	—	—	—	—	—	—						—	—	—	◪	
Environ cont	—	—	—	—	—	—	—	—	—	—						—	—	—	◪	
Launch escape	—	—	—	—	—	—	—	—	—	—						—	—	—	—	—
Comm *	▲	▲	▲	▲	▲	—	▲	—	▲	▲						▲	—	—	▲	▲
Oprnl instr (sys mgt disp & cont)	◪*	◪*	◪	◪	▲	◪◪	◪	◪	◪	◪						◪	◪	◪◪	◪	◪
Earth lndg	—	—	—	—	—	—	—	—	—	—						—	—	—	—	◪
Separ (SM/CM, SM/S-3 & LEM/S-3)	—	—	—	—	◪◪	—	—	—	—	—						—	—	—	—	◪
Struct	—	—	—	—	—	—	—	—	▲	—						▲	—	—	—	▲*
SM propul eng	—	—	—	—	—	—	◪	—	—	—						—	—	—	—	—
SM propel feed	—	—	—	—	—	—	◪	—	—	—						—	—	—	—	—
Crew equip *	▲	▲	▲	▲	▲	▲▲	▲	▲	▲	▲						▲	▲	▲	▲	▲
LEM																				
Nav (OMU & comput's)									▲		—	▲	—	—	▲	—				
Guid (steering cmds)									●		—	◪	—	—	●	—				
Stab & cont									◪		▲	◪	△	—	◪	▲				
React cont									◪		—	—	—	—	—	—				
Comm *									◪		▲	▲	▲	▲	▲	▲				
Environ cont									◪		—	—	—	—	—	—				
Separ (TO to LND)									—		—	—	—	—	◪	—				
Elect pwr									◪		—	—	—	—	◪	—				
Lunar tchdwn--gear									◪		—	—	▲	—	—	—				
Propul eng									◪		—	—	—	—	◪	—				
Propel feed									◪		—	—	—	—	◪	—				
Oprnl instr (sys mgt disp & cont)									◪		▲	◪	▲	◪	◪	▲				
Scientific instr									—		—	—	—	▲*	—	—				
Struct									—		—	—	—	▲	—	—				
Crew equip *									▲		▲	▲	▲	▲	▲	▲				

NOTES:

● Manual enabling with capability for verification and correction.
▲ Manual function with capability for verification and correction.
◪ Programmed enabling with manual back-up.
△ Manual function.
— Automatic system with manual back-up for decisions and switching.
* System or function treated not critical to mission success.

Fig. III-5. Man-Machine Performance Interface, LOR

DF Man-Machine Performance Interface by Mission Steps

Spacecraft Systems and Mission Steps	1st Stage	2nd Stage	Earth Orbit Coast	3rd Stage (2 Burns)	Midcourse (2 Correc)	Trans-Lunar Coast	Lunar Orbit Retro	Lunar Orbit Coast	Descent to Moon	Landing On Moon	Lunar Operation	Lunar Launch	Lunar Orbit Escape	Midcourse (2 Correc)	Trans-Earth Coast	Earth Entry & Landing
A. CM and SM																
Nav (OMU & comput's)	—	—	▲	—	—	▲	—	▲	▲	—	—	▲	—	—	▲	▲
Guid (steering cmds)	—	—	—	◪	◪◪*	—	◪	—	◪	—	—	●	◪	◪◪*	—	—
Stab & cont	—	—	◪*	◪	◪◪	◪*	◪	◪	◪	△	—	◪	◪	◪◪	◪*	◪
React.cont (CM & SM)	—	—	—	—	—	—	—	—	—	—	—	—	—	—	◪	—
Elect.pwr	—	—	—	—	—	—	—	—	—	—	—	—	—	—	◪	—
Environ cont	—	—	—	—	—	—	—	—	—	—	—	—	—	—	◪	—
Launch escape	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Comm *	▲	▲	▲	▲	—	▲	—	▲	▲	▲	▲	▲	—	—	▲	▲
Oprnl instr (sys mgt disp & cont)	◪*	◪*	◪	◪	◪◪	◪	◪	◪	◪	▲	◪	◪	◪	◪◪	◪	◪
Earth lndg (CM)	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	◪
Separ (CM/SM & SM/LEM)	—	—	—	—	—	—	—	—	—	—	—	◪	—	—	—	◪
Struct	—	—	—	—	—	—	—	—	—	—	▲	—	—	—	—	▲*
SM propul eng	—	—	—	—	—	—	—	—	—	—	—	◪	—	—	—	—
SM propel feed	—	—	—	—	—	—	—	—	—	—	—	◪	—	—	—	—
Crew equip *	▲	▲	▲	▲	▲▲	▲	▲	▲	▲	▲	▲	▲	▲	▲▲	▲	▲
LLM																
Scien instr *				—	—	—	—	—	—	—	▲*					
Lunar tchdwn				—	—	—	—	◪	—	▲	—					
Separ (LLM to S-3)				◪	—	—	—	—	—	—	—					
Struct				—	—	—	—	—	—	—	▲*					
Environ cont				—	—	—	—	—	—	—	▲					
Propul eng				—	◪	—	—	—	—	—	—					
Propel feed				—	◪	—	—	—	—	—	—					

Fig. III-6. Man-Machine Performance Interface, DF

aborts initiated from various phases of the mission profile. In general, the abort maneuver sequence is either the same for both the LOR and DF, or the abort requires normal mission return maneuvers. One significant difference between the two configurations is that, prior to the lunar descent phase of the mission, the LOR system has an additional propulsion system which provides a redundant abort propulsion capability. In both techniques, transearth return time can be reduced for emergency purposes of 10 to 15 hours by selecting the maximum velocity return trajectory limited by the earth re-entry capability of the Command Module.

2. Functional Analysis of Selected Emergencies

The situations selected for analysis were as follows:

(1) Meteoroid penetration of the pressure cabin at 22 hr after lunar landing. The size of the orifice is 1/2 in. in diameter.

(2) Lunar landing engine failure occurring at the 1000-ft hover condition over the lunar surface. The indication of the malfunction is a loss of chamber pressure.

(3) Partial electrical power failure occurring 4 hr after lunar landing. One crew member is out of the vehicle exploring the lunar surface. In the DF mode two of the three fuel cell batteries have failed, and in the LEM two of two fuel cell batteries have failed.

(4) Twenty hrs after lunar landing one crew member is disabled and incapacitated for the return.

(5) Environmental control system failure occurring during the initial lunar orbit insertion (partial failure of cabin and suit circulation). The blower overheats, causing atmospheric contamination, cabin temperature rise to 115°, and reduction in atmospheric regeneration.

(6) Partial guidance system failure during second translunar midcourse correction. The guidance system fails to cut off engine and all subsequent cutoffs are manual. Manual engine cutoff is 5 sec late for the posigrade correction.

These cases were considered for both LOR and DF. In addition, a seventh case was selected for the LOR--that of a LEM propulsion failure in the low parking orbit after lunar launch, resulting in inability to transfer the LEM to the rendezvous altitude. No parallel noncatastrophic case exists for the DF mode.

The initial conditions and the functional analysis for these emergency operations are summarized in Table III-2. No repair possibilities were included in this portion of the study; repair and maintenance considerations are discussed separately in Section VII.

[redacted]

TABLE III-1

Abort Maneuver Profile--LOR and DF

	Abort Maneuver Sequence									
Mission phase abort initiated	Launch vehicle shut-down	CM separates using launch escape sys-tem propul-sion	Spacecraft passively circumnavi-gates moon	SM propul-sion inserts into earth landing tra-jectory	Lunar orbit insertion by either lunar land-ing or take-off propul-sion	Transearth insertion by either lunar land-ing or SM propulsion	Trajectory correction either by lunar land-ing or SM propulsion	CM sepa-rates near earth using CM/ reaction control	CM re-enters earth atmos-phere and lands	Normal mis-sion return pro-file*
Launch pad through first-stage burnout	X	X							X	
Second stage burn to earth orbit	X			X				X	X	
Earth orbit				X				X	X	
Trans-lunar in-sertion to near moon	X			X			X	X	X	
Near moon to lunar orbit insertion			X				X	X	X	
Lunar orbit in-sertion through lunar orbit						X	X			X
Descent from lunar orbit to touchdown					X					X
Sub-sequent to lunar landing										X

*Transearth return time can be reduced 10 to 15 hrs by selecting the maximum design velocity trajectory if return time is critical.

[redacted]

TABLE III-2

Emergency Abort Functions

PROCEDURE/SEQUENCE				DF	LOR
I. Meteoroid Penetration of Cabin					
Initial conditions: occurs 22 hr after lunar landing; no repair possible; 1/2-in. dia hole.					
(1)	Cabin penetrated by meteoroid	†T = 0	‡T = 0	x	x
(2)	Pressure drop sensed and crew alerted	†T = +11 sec	‡T = +16 sec	x	x
(3)	Secure suits (2 min)	†T = +2 min - 11 sec	‡T = +2 min - 16 sec	x	x
(4)	Activate suit supply system	†T = +2 min - 26 sec	‡T = +2 min - 31 sec	x	x
*(5)	Secure cabin pressurization system	†T = +2 min - 41 sec	‡T = +2 min - 46 sec	x	x
(6)	Using suit ECS operate DF to earth landing			x	
(7)	Operate LOR using suit ECS through rendezvous and docking				x
(8)	CM operator dons suit				x
(9)	Decompress CM				x
(10)	Crew transfer				x
(11)	Recompress CM				x
(12)	Separate LEM and continue LOR in normal operation				x

*Pressure drops below that necessary for minimum crew capability for DF at T = +2 min, 55 sec (2.2 psia 100% O_2) for LOR at T = + 3 min, 24 sec.

†DF
‡LOR

[redacted]

TABLE III-2 (continued)

	PROCEDURE/SEQUENCE		DF	LOR
II.	Landing Engine Failure			
	Initial conditions: occurs at 1000-ft hover over lunar surface; no repair possible; engine failure/loss of chamber pressure.			
(1)	Thrust chamber fails	T = 0, Alt = 1000 ft	x	x
(2)	Pressure drop sensed and crew alerted	T = < 1/2 sec	x	x
(3)	Initiate abort (shuts down engine, separates, starts second engine, switches guidance mode, etc.)	T = < 4 sec, Alt > 920 ft	x	x
(4)	Automatic powered ascent--start at	T = 65 sec, ALT > 900 ft	x	x
(5)	LEM normal ascent to low parking orbit, ascent to rendezvous and return			x
(6)	DF normal ascent to parking orbit and return		x	
III.	Partial Power Failure			
	Initial conditions: occurs 4 hr after lunar landing; no repair possible; one man on lunar surface 1/2 mile distant; for DF, 2 of 3 FCB failed; and for LEM, 2 of 2 failed.			
(1)	Crewman senses power failure, T = 0		x	x
(2)	Power consumption reduced to minimum (see Notes 1 and 2 at end of table)		x	x
(3)	LEM switches to ascent power supply			x
(4)	Crewman notified to return to ship (see Notes 1 and 2 at end of table)	T = 1 min to T = 16 min	x	x
(5)	Prepare for abort (see Notes 1 and 2 at end of table)		x	x

[redacted]

TABLE III-2 (continued)

	PROCEDURE/SEQUENCE		DF	LOR
(6)	DF ascent and return sequence is normal, except for restrictions in Note 1 at end of table		x	
(7)	LOR ascent up to rendezvous is normal, except for restrictions in Note 2 at end of table			x
(8)	Attitude control during rendezvous and docking is manual (see Note 2 at end of table)			x
(9)	Crew transfer via air lock with back packs			x
(10)	LEM separation and CSM return is normal			x
IV.	One Man Disabled			
	Initial conditions: occurs 20 hr after lunar landing; man has broken leg 1/2 mile distant; incapacitated for return.			
(1)	Accident occurs	T = 0	x	x
(2)	S/C notified of accident	T = + 1 min	x	x
(3)	S/C is secured and decompressed	T = + 2 min	x	x
(4)	Man in S/C proceeds to injured man	T = + 2 min to T = + 22 min	x	x
(5)	Man is retrieved and returned	T = + 22 min to T = + 52 min	x	x
(6)	Man is carried up S/C and secured inside	T = + 52 min to T = + 67 min	x	x
(7)	S/C is recompressed		x	x
(8)	Suit is removed and first-aid rendered		x	x
(9)	LOR crew performs a normal but one-man ascent and rendezvous			x
(10)	Crew transfer with injured man to CM			x
(11)	LOR crew performs a normal but two-man return			x

TABLE III-2 (continued)

PROCEDURE/SEQUENCE	DF	LOR
(12) DF crew performs at normal but one man ascent and return	x	
V. Environmental Control Systems Failure		
Initial conditions: occurs during initial lunar orbit insertion; partial failure of cabin and suit circulation; blower overheating causes atmosphere contamination; results in cabin temperature rise to 115° ; reduction in atmosphere regeneration; no repair possible.		
(1) Blower motors fail partially	x	x
(2) Crew senses failure	x	x
(3) Crew secures pressure suits and switches to back packs	x	x
(4) ECS cabin and suit circulation system is turned off	x	x
(5) Maneuver is completed	x	x
(6) Cabin is decompressed to remove atmosphere contamination	x	x
(7) Cabin is recompressed	x	x
(8) ECS is turned on if possible (partially); crew operated in "open face plate mode"	x	x
(9) Crew prepares for abort	x	x
*(10) Landing stage(s) are jettisoned	x	x
(11) Transearth insertion and return is normal maneuver	x	x

*LOR crew could effect a repair of ECS by getting parts from LEM system; however, mission is still aborted.

TABLE III-2 (continued)

	PROCEDURE/SEQUENCE	DF	LOR
VI.	Guidance System Failure		
	Initial conditions: occurs during second translunar midcourse correction; guidance fails to cut off engine and all subsequent cutoffs; engine cut off manually 5 sec late; correction was posigrade.		
(1)	Engine fails to shut down, T = 0	x	x
(2)	Crew senses failure, T = + 1 sec	x	x
(3)	Crew manually commands shutdown, T = + 5 sec	x	x
(4)	Crew prepares for abort, repositions spacecraft	x	x
(5)	Inverse corrective maneuver is accomplished	x	x
(6)	S/C circumnavigates moon and begins transearth flight	x	x
*(7)	Landing stage(s) are jettisoned	x	x
(8)	Transearth midcourse corrections and return is normal	x	x
VII.	LO Rendezvous Propulsion Failure (LOR)		
	Initial conditions: occurs just prior to LO rendezvous after ascent coast; no repair possible; reaction control thruster failure.		
(1)	Thrust chamber fails T = 0		x
(2)	Pressure drop sensed and crew alerted T = < 1/2 sec		x
(3)	LEM notifies CSM and failure, T = 5 sec		x
(4)	CSM readies for rendezvous maneuver, T = 1 min		x

*LOR crew could effect a repair by getting parts from LEM; however, mission is still aborted.

TABLE III-2 (continued)

	PROCEDURE/SEQUENCE	DF	LOR
(5)	CSM retrogrades into rendezvous, T = 5 min		x
(6)	CM docks with LEM		x
(7)	Crew transfer		x
(8)	CSM separates from LEM		x
(9)	CSM injects into LO (posigrade)		x
(10)	CSM performs a normal TE insertion and return		x

NOTES

CONDITIONS/RESTRICTIONS DUE TO POWER LIMITATIONS

NOTE 1, DF

1. Increased power separates management-time sharing.
2. All telemetry and communications off except for DSIF or Near Earth-voice.
3. Environmental control system is turned off during all maneuvers (temperature may rise).
4. Lighting is reduced to two-thirds.
5. Displays are kept on or activated only as needed.

NOTE 2, LOR

1. Increased power separates management-time sharing function.
2. Telemetry and communications off except for VHF/voice. DSIF/TV is used for first 6 min of ascent only.
3. Radar altimeter not used.
4. Manual attitude control during coast and rendezvous.
5. Crew uses pressure suits and back packs. (LEM cabin and suit ECS circuits are off.)
6. Lighting is reduced to two-thirds.

IV. CREW PERFORMANCE ANALYSIS

The methods and the data utilized to evaluate crew performance within the LOR and DF modes are presented in this section. The man-machine system factors considered as potential influences on crew performance are first defined and discussed briefly. Next the system assumptions, mathematical considerations, and crew task assignments are presented, followed by the results and discussion of the crew performance analysis.

A. FACTORS INFLUENCING PERFORMANCE

The following eight pertinent factors were considered as possible influences on crew performance during either the LOR or DF modes:

(1) Long term monitoring performance.

(2) Restrictive volume.

(3) Task complexity.

(4) Biomechanical or environmental stress.

(5) Anxiety or general psychological stress.

(6) Continuous complex task performance.

(7) Fatigue.

(8) Sensory deprivation.

A review of work already accomplished in previous studies indicated that three of these factors--continuous complex task performance, fatigue, and sensory deprivation--were either no problem or could be controlled by appropriate manipulation of the crew or system within the constraints of the present study. The remaining five factors were all studied more thoroughly as to possible effect on crew performance. The following is a brief description and discussion of each of the eight factors, several of which are grouped for discussion convenience.

1. Long Term Monitoring Performance

Previous studies on manned lunar systems have indicated that 65% to 75% of the total mission time is concerned with behavior which is essentially monitoring in nature. The monitoring encompasses the following tasks:

(1) Detection of malfunctions.

(2) Detection of changes in system status.

(3) Periodic scanning of critically displayed system information.

(4) Systems management or the evaluation of onboard systems and information.

The detection and scanning tasks are considered to take place throughout the entire mission; their difficulty as a crew task is dependent upon the amount and different types of information to be detected. The systems management tasks occur periodically throughout the entire mission.

A host of experimental studies and data available from the operational performance of radar operators, sonar operators, etc., indicate monitoring performance to be easily degraded as a function of time on the task (Refs. 7 and 8). Reference 9 has indicated that monitoring performance may be considered as a special case of decision-making rather than a discrete behavior entity itself. Further, monitoring appeared in the present studies not to be primarily dependent upon time on the task, but rather upon the criteria utilized by the operator during the monitoring period. These studies further indicated that by manipulation of the criteria different performance levels could be achieved. Also, there appeared to be a large subject variability. Some subjects were able to adopt the proper criteria at the proper time while other subjects were not. These criteria are currently being investigated as to their relationship with different levels of motivation. However, data in the general area of decision making indicate motivation to be an important variable. Therefore, it would appear that with proper training in decision-making concerning the various systems, the monitoring detection tasks performed by an astronaut crew should degrade insignificantly during a mission of eight days or less. This indication is further enhanced if the mission duty cycle consists of duty periods of no longer than 3 hr and if music or other devices are utilized to offset any boredom due to a low sensory input into the monitoring crew member.

Consideration of simulation data (Ref. 6) bears out the above statements. During the three lunar landing simulation studies conducted with trained test pilot personnel who were extremely well motivated, detection monitoring was performed at a consistently high level throughout each flight. During the 75-hr and 164-hr flight simulations, the duty periods for each crew member averaged 2.2 hr. The crew utilized an onboard music system during the monitoring phase to relieve boredom. The use of this system apparently did not interfere with onboard performance. The performance of the crew was excellent as indicated by rapid detection of malfunctions, aborts, and other events which occurred during the flights.

The class within monitoring which is called systems management is primarily concerned with procedural tasks involving each of the subsystems. These tasks not only encompass monitoring capabilities but also to some extent decision and switching capabilities. The simulations previously mentioned (Ref. 6) indicated some gradual loss in this type of capability during the flight. The primary reason given for this apparent degradation was the effect of lack of practice between the last training period and the first time the task had to be performed. Whether these performance deficits might also be due to confinement or restrictive environment was not entirely obvious. However, it is believed that some component of this degradation might be charged to the restrictive environment.

The discussion thus far has primarily been concerned with the LOR mode since our simulation data was obtained on such a system. It is believed that monitoring detection performance would not be affected by more restrictive volume, even for the considerably reduced volume associated with the DF configuration (80 cu ft for the two men). It is believed, however, that systems management performance would be more affected by the more restrictive volume. This belief is based on the very drastic effects noted in confinement situations at very reduced volumes (Refs. 10 and 11), even though these data do not meet the requirements of proper sample population and task realism. A two-man confinement study conducted at the Ames Research Center, which apparently showed an increasingly improved performance with time, may seem initially to have contradicted this conclusion. However, since the confinement volume was considerably larger than that of the present DF configuration, and since the performance improvement indicates that training prior to the confinement may have been inadequate, it appears that the results of the Ames study are more indicative of goal gradient behavior and learning effects than they are of volume restriction.

In conclusion, it appears that there is a relationship between systems management performance and restrictive volumes. Precisely why a degradation should occur at the lower volumes is not clear. It might be due to general psychological stress or general somatic discomfort. The precise shape of the curve indicating its long term effect will be discussed later in this section.

2. Restrictive Volumes and Sensory Deprivation

It is apparent from the latter portion of the discussion of monitoring performance that one of the major effects on monitoring performance during long term flight appears due to the amount of crew compartment volume available. This has, indeed, developed into a major assumption of the present study and deserves some explanation. The effects of restrictive volume must first be differentiated from the effects of sensory deprivation. Within the available experimental literature, it is difficult to make this differentiation since a majority of the studies confound both sensory deprivation and confinement variables. It appears, however, that the effects on performance are different for each of these factors.

The effects of sensory deprivation on human performance can be quite drastic. Not only is task performance affected but also general psychological well-being (Refs. 12, 13 and 14). In consideration of the two systems utilized in the present study, no effects due to sensory deprivation are anticipated. First, although there is a partial reduction of sensory input into the human system, the inputs are not eliminated. Second, the results of the simulation reported in Ref. 6, which are directly applicable to the cases under study, indicated no effects due to sensory deprivation.

The effects due to confinement are not as dramatic as those experienced with sensory deprivation situations (Refs. 5 and 15). However, there appears to be a volumetric level at which some performance deficits occur. In reviewing the literature, this volume does not appear as a clear entity, but we can assert from various simulation studies (Refs. 5 and 15) that with all volumes below 400 cu ft for two men, some deficits will occur. The important variables are time of confinement, volume, and crew composition (Ref. 6). The effects may not be as drastic as halucinatory experiences or psychotic behavior but may be such subtle factors as "forgetting" learned performance, somatic complaint, and perservative errors in performance. It is with these types of performance deficits that the present study is concerned.

For the present study, therefore, sensory deprivation has not been considered as a potential cause of performance degradation. However, time of confinement in restrictive volumes has been considered as an important variable, not only in monitoring performance but also in other types of performance. The method of evaluating performance deficits due to restrictive volumes will be presented later in this section.

3. Task Complexity, Continuous Task Performance, and Fatigue

Task complexity. Another major variable which must be considered as a potential source of performance degradation is task complexity. In the analyses of the two systems under consideration, four general categories of tasks (Ref. 16) have been determined, as follows:

(1) Detection monitoring tasks

(2) Systems management tasks

(3) Switching tasks

(4) Control tasks.

Detection monitoring and systems management tasks have already been discussed. The switching and control tasks must also be considered as to their potential complexity. An analysis revealed that the switching tasks and control tasks were affected in the same gradual manner as the systems management tasks. Monitoring was separated because it was the task most constantly and frequently performed.

The complexity of these categories of tasks for the LOR and DF modes was obtained by rating each of these tasks as they occurred during the mission. Four raters judged these tasks.

TABLE IV-1

Rating Scale for Task Complexity

Rating	Meaning
-3	Very very easy
-2	Very easy
-1	Easy
0	Average
1	Difficult
2	Very difficult
3	Very very difficult

For all tasks the initial rating on a five point scale was performed by two raters who were quite experienced on the lunar mission, systems, and crew capabilities. Subsequent to this initial rating and in order to gain a more logical spread in the ratings, two other raters resolved any discrepancies from the initial ratings and transposed the data into a 7-point scale as seen in Table IV-1. The final distribution of all tasks to be performed during the LOR and DF modes is shown in Table IV-2.

Two items are apparent from inspection of Table IV-2. First, in both the LOR and DF cases, at least 80% of all tasks performed were judged of average or less than average difficulty. Second, there is an apparent difference in the number of tasks performed by the crew in the LOR and DF modes. This difference is further intensified when an additional 102 tasks are added to the LOR mode to be performed within the Command Module during the orbit coast phase. The final total number of tasks for each mode is then 448 tasks for the LOR and 327 tasks for the DF.

TABLE IV-2

Distribution of Scores on 7-Point Scale for LOR and DF Modes

Rating	LOR	Direct
-3	90	92
-2	39	36
-1	44	42
0	125	138
1	40	16
2	8	1
3	0	2
Total	346	327

Thus, task difficulty in both modes may be judged average or of less than average difficulty based upon tasks currently performed on a variety of manned systems. Further, the number of tasks to be performed in the LOR is higher than the number of tasks to be performed in the DF mode.

The various discrete tasks within each of the categories and their difficulty ratings are shown in Table IV-3.

TABLE IV-3

Task Category

Systems Management	Complexity Rating	Switching	Complexity Rating	Control	Complexity Rating
Communication	-3	Data entry	-3	Transfer to LEM	+1
Log check	-2	Switch to different mode	0	Firing initiation	+1
Record data	-2	Enable	0	Attitude control	+2 or +3
Systems check	-1	Alignment	+1	Translation control	+2
Obtain information	-1	Star fix	0		
Determine trajectory	-1				
Compare data	0				

Detection monitoring tasks were not rated in the same manner as the other tasks. As stated earlier, detection monitoring is a continuous process throughout the entire mission. Further, it is highly dependent upon the degree of automaticity and the type of display system utilized. In order to estimate the difficulty of detection monitoring tasks, it was decided that some relationship between the number of display elements to be monitored and visual scans would be the best measure. Further, this would allow for an estimate of detection monitoring workload. Therefore, it was assumed that for high detection monitoring performance, one visual scan every

10 minutes for the duration of the mission was required. By counting each subsystem that needed to be monitored, the number of elements monitored could be obtained. Therefore,

(a)
- Total mission time for LOR Command Module = 183 hr
- 6 scans per hr for LOR
- 30 elements to scan for LOR Command Module
- (183)(6)(30) = 32,940 job elements for the CM mission

(b)
- Total mission time for LEM = 51 hr
- 6 scans per hr for LEM
- 18 elements per scan
- (51)(6)(18) = 5508 job elements for LEM

(c)
- Total mission time for DF = 183 hr
- 6 scans per hr for DF
- 22 elements to be scanned for DF
- (183)(6)(22) = 24,156 job elements for DF

It therefore appears that the LOR mode requires more detection monitoring activity than the DF. However, it has been stated earlier in this chapter that detection monitoring did not seem affected by long term flight (Ref. 6), and with the exception of some minor modifications the LOR mode used for the analysis in the present study was the same one evaluated during the previously mentioned simulations.

Directly related to the categorization of tasks and evaluation of task difficulty is the consideration of crew workload. For the purposes of this study, primary concern is given to significant differences in crew workload between the LOR and DF modes, or between either of these and some obtained empirical level.

A number of general rules of thumb are available for the assignment of tasks to determine crew workload which correlate many aspects of the man-machine relationship within any system. These are as follows:

(1) Tasks should be assigned so that at least 80% of the crew member's capability remains to handle emergencies (Ref. 6).

(2) In long term flight, free time allowed should be sufficient for other activities, yet limited to safeguard against boredom effects.

(3) Workload level is dependent on the excellence of the display system. Therefore a proper and usable display system is required to yield reasonable workload levels during critical flight phases (Ref. 6).

(4) Workload level is also dependent on the duty cycle utilized. (Discussed later in this section).

Table IV-4 presents the total number of job elements to be performed by the crew in each lunar landing system for various discrete phases. Figure IV-1 presents a diagramatic representation of the same data.

TABLE IV-4

Total Number of Job Elements To Be Performed per Minute

Mission Time (hr-min)	Phase	LOR Mode Total Number of Job Elements/Min	DF Mode Total Number of Job Elements/Min
T + 0:12 to T + 1:03	Earth orbit coast to translunar insertion	7.573	5.129
T + 1:03 to T + 4:40	Translunar insertion to correction 1	7.389	5.025
T + 4:40 to T + 16:50	Correction 1 to 2	3.437	2.099
T + 16:50 to T + 34:50	Correction 2 to 3	2.494	1.756
T + 34:50 to T + 50:05	Correction 3 to 4	2.776	1.992
T + 50:05 to T + 65:30	Correction 4 to 5	2.208	1.489
T + 65:30 to T + 66:30	Correction 5 to lunar orbit insertion	3.833	5.283
T + 66:30 to T + 70:12	Lunar orbit insertion to landing	6.274	5.044
T + 70:12 to T + 71:00	Landing to scientific mission	12.652	9.572
T + 116:00 to T + 119:48	Prelaunch to transearth insertion	4.940	5.197
T + 19:48 to T + 126:15	Transearth insertion to correction 1	4.739	3.372
T + 126:15 to T + 135:50	Correction 1 to 2	3.046	2.164
T + 135:50 to T + 152:20	Correction 2 to 3	2.322	1.623
T + 152:20 to T + 168:50	Correction 3 to 4	1.504	1.664
T + 168:50 to T + 179:20	Correction 4 to re-entry correction	3.143	2.221
T + 179:20 to T + 183:00	Re-entry correction to recovery	5.491	3.829

[redacted]

LEGEND

1 Earth orbit coast to translunar insertion
2 Translunar insertion to Correction 1
3 Corrections 1 to 2
4 Corrections 2 to 3
5 Corrections 3 to 4
6 Corrections 4 to 5
7 Correction 5 to lunar orbit insertion
8 Lunar orbit insertion to landing
9 Landing to scientific mission
10 Prelaunch to transearth insertion
11 Transearth insertion to Correction 1
12 Corrections 1 to 2
13 Corrections 2 to 3
14 Corrections 3 to 4
15 Correction 4 to re-entry correction
16 Re-entry correction to recovery

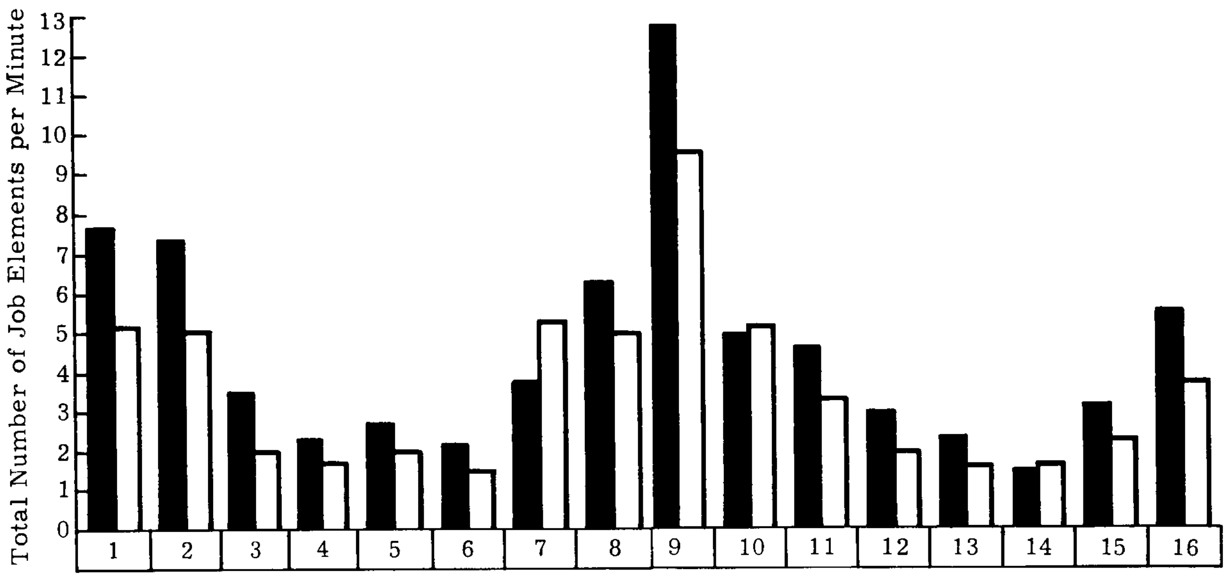


Fig. IV-1. Comparative Workload Per Minute

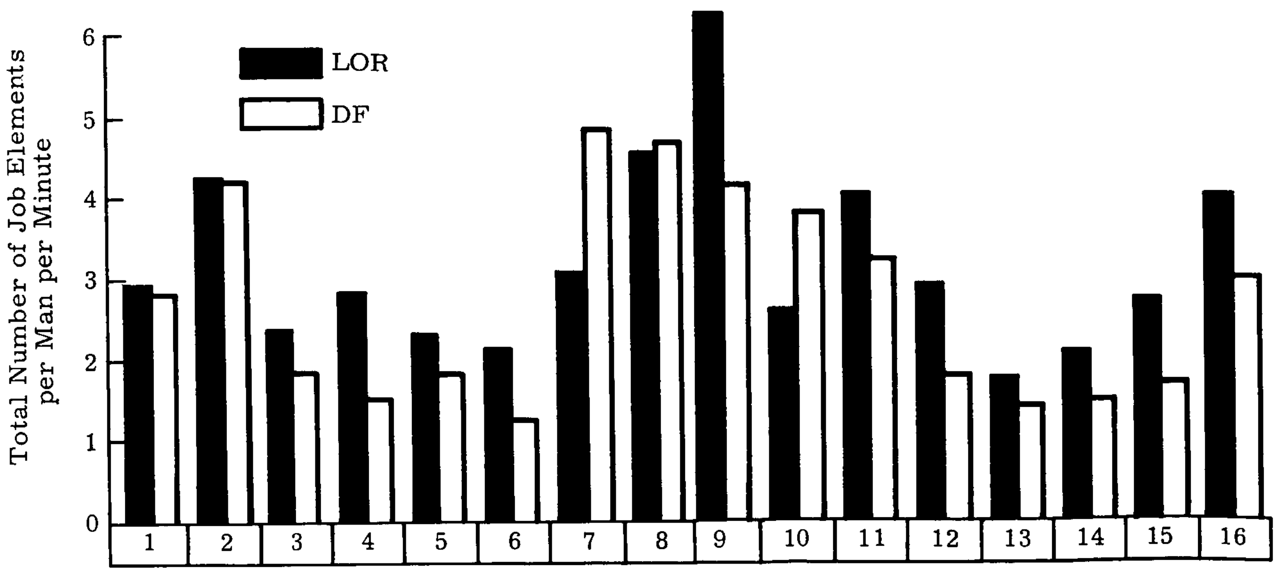


Fig. IV-2. Comparative Workload Per Man Per Minute

[redacted]

Workoad has been expressed in both the table and the figure as a function of job elements. Job element is defined as any psychomotor or perceptual act required for completion of a particular task. Thus, the number of job elements is dependent upon the type of display system utilized.

As can be seen from Table IV-4 and Fig. IV-1, the workload within the LOR mode is higher than in the DF mode. However, these data do not take into account the number of crew members available to perform the tasks within various phases. Table IV-5 and Fig. IV-2 present the total number of tasks to be performed per man per minute for each lunar landing mode. Inspection of this table and figure indicates somewhat less of a difference between the two modes, but the workload per man is still higher in the LOR than in the DF.

The higher LOR workload level comes about because the larger panel area and greater crew mobility made possible--and desirable--the assignment of more crew functions than in the DF case. In the latter mode, the inability to display proper information to the crew necessitated greater task automation. In addition, the existence of a separate landing vehicle in the LOR mode further increased the number of crew tasks. Not included in this tabulation but discussed in Section VII is an additional group of possible tasks associated with repair and maintenance; again, the increased volume in the LOR spacecraft would lead to a larger assignment of crew tasks in this mode.

Figure IV-2 indicates in two instances a much larger workload in the DF mode than in the LOR mode. These are during the phases from the last translunar correction to lunar orbit insertion and from lunar prelaunch to transearth insertion. The additional workload in both of these situations is due to checkouts of onboard systems, which three men perform in the LOR case as compared with two men in the DF case. Further, these data do not indicate the workload of the Command Module in lunar orbit. The tasks to be performed by the crew member in the CM are stereotyped and constant; nevertheless, the addition of this workload level during these periods would again indicate the LOR mode having a higher workload.

It is of interest to compare the workload levels for both the LOR and DF modes with some empirically derived data. The previously mentioned simulation (Ref. 6) utilized the LOR mode, with a one-man excursion vehicle instead of the two-man excursion vehicle considered in the present study. The results of comparison with the simulation data indicated the following:

(1) The simulation workload levels expressed in job elements per man per minute were considerably higher than those determined in the present study (i.e., 7.250 in the earth orbit coast to translunar insertion phase and 12.411 in the lunar orbit insertion to lunar landing phase). These measures were, of course, obtained from actual times during which the crew performed the tasks in the simulations, as opposed to the estimated times used in the present study.

(2) Performance of the assigned tasks was excellent. There was a general belief among the pilots that an overload existed, particularly during the lunar landing and lunar takeoff phases. However, this overload was believed attributable to the difficult display panel scan pattern required of the crew during dynamic flight phases.

TABLE IV-5

Total Number of Job Elements to be Performed per Man per Minute

Mission Time(hr/min)	Phase	LOR Mode Total Number of Job Elements/Man/Min	Direct Flight Mode Total Number of Job Elements/Man/Min
T + 0:12 to T + 1:03	Earth orbit coast to translunar insertion	2.945	2.718
T + 1:03 to T + 4:40	Translunar insertion to correction 1	4.253	4.238
T + 4:40 to T + 16:50	Correction 1 to 2	2.349	1.902
T + 16:50 to T + 34:50	Correction 2 to 3	2.279	1.606
T + 34:50 to T + 50:05	Correction 3 to 4	2.326	1.827
T + 50:05 to T + 65:30	Correction 4 to 5	2.171	1.321
T + 65:30 to T + 66:30	Correction 5 to lunar orbit insertion	3.108	4.883
T + 66:30 to T + 70:12	Lunar orbit insertion to landing	4.503	4.158
T + 70:12 to T + 71:00	Landing to scientific mission	6.326	4.214
T + 116:00 to T + 119:48	Prelaunch to transearth insertion	2.712	3.906
T + 119:48 to T + 126:15	Transearth insertion to correction 1	4.092	3.311
T + 126:15 to T + 135:50	Correction 1 to 2	2.987	1.888
T + 135:50 to T + 152:20	Correction 2 to 3	1.891	1.468
T + 152:20 to T + 168:50	Correction 3 to 4	2.141	1.504
T + 168:50 to T + 179:20	Correction 4 to re-entry correction	2.780	1.970
T + 179:20 to T + 183:00	Re-entry correction to recovery	4.004	2.969

Therefore, it appears that the workload levels estimated for both the LOR and DF modes do not constitute an important factor in crew performance degradation since they are both considerably below the levels obtained from simulation data where performance was found to be excellent. Further, the difference between the workload levels of the LOR and DF modes is not considered to be of sufficient magnitude to justify a comparison of performance on this variable.

Continuous task performance and "time critical" tasks. Another important factor which must be considered is continued performance of various complex tasks. In the preceding discussion of the rating of task difficulty, a number of tasks were shown to be rated as very difficult. However, the difficulty of these tasks as expressed in the rating system does not present the entire picture. The difficulty rating scale is based upon the inherent difficulty of the task, without regard to other factors such as time on the task. A requirement to perform a difficult task continuously for a considerable period of time during the mission might be expected to cause a performance degradation. The analysis conducted during this study, and the available simulation data, both indicate that there are no instances of continuous difficult task performance for periods longer than one hour with either the LOR or the DF mode. Therefore, on the basis of this finding, the crew should have little or no difficulty in maintaining high performance even with the most difficult tasks, provided there is no interaction effect from another variable.

The consideration of complex task performance has, however, indicated another area of performance which must be given attention. This is performance on those tasks which are considered "time critical." "Time critical" tasks are those which, although performed for a relatively short period of time, require a very high level of performance (or a very close tolerance) because of their importance to the mission. A number of such "time critical" task periods have been identified. These are:

(1) Lunar landing--braking, hovering, and landing for both modes.

(2) Lunar launch--for both modes.

(3) Lunar orbit rendezvous--LOR mode.

(4) Transearth insertion--both modes.

(5) Earth re-entry--both modes.

These "time critical" tasks were given particular emphasis during the study, and will be covered more fully in the discussion of results.

Since the level of performance required, or system tolerance, is an important variable that must be considered along with performance degradation and task difficulty, a 3-point rating scale was constructed and the level of performance required by the crew based on required system tolerances was judged in the same manner as task difficulty. This scale is presented in Table IV-6. It should be noted that the difficulty scale and the level-of-required-performance scale were considered to be independent and were rated accordingly. In constructing this scale, one primary assumption was utilized. This assumption was that no task would be assigned to the crew if, in consideration of his expected performance, man could not meet an 85% correct performance level, as required by the system. The mathematical relationship between level of required performance, task difficulty and performance degradation will be discussed later in this section.

TABLE IV-6

Scaled Values for Level of Required Performance

Scaled Value	Meaning
-1	100 to 95% correct performance required
0	95 to 90% correct performance required
+1	90 to 85% correct performance required

Fatigue. The possible effect of fatigue on performance is related to workload. The analysis of the two systems indicated that two possible variables may be considered under the heading of fatigue. One variable is concerned with subjective feelings of fatigue caused by confinement situations and other types of psychological stress. This variable or the components of this variable which contribute to performance degradation have been included in the restrictive volume factor.

The other variable of fatigue which is an important consideration is that caused by an improper duty cycle. The analysis performed on both the LOR and DF modes has indicated that a proper duty cycle may be developed for each. With the LOR mode, a 26-hr repeatable cycle could be utilized which would have the following characteristics:

(1) An average on-duty time for the mission in the Command Module of 2 hr.

(2) An off-duty period prior to and after a sleep period.

(3) Two sleep periods, of approximately 4 hr each during each 26 hr.

(4) During the stay on the lunar surface within the LEM, either a 4-on/4-off or a 4-on/2-off schedule would be satisfactory.

(5) Within the Command Module during lunar orbit coast, the single crew member could maintain a 4-on/2-off schedule, and he would be on call for emergencies. Barring emergencies, his tasks during this period are routine as to communication, monitoring, and systems management.

For the direct mode a 4-on/4-off or 4-on/2-off schedule could be developed which would satisfy the mission requirements as well as crew performance considerations. All of these duty cycles have to some extent been verified experimentally, with the LOR duty cycle having been verified under more realistic conditions (Refs. 4, 5, 6 and 17).

The difference in expected performance between the two modes as a function of the duty cycles appears insignificant. The difference, if any, favors the LOR mode because of more off-duty time and possibly shorter duty periods. However, in either case, performance should not be degraded by either duty cycle for the 183-hr mission under consideration.

Summary. The above discussions can be summarized as follows:

(1) All crew tasks were divided into 3 categories (not including detection monitoring). The categories and the specific tasks contained within them were rated on a 7-point scale as to task complexity. The task complexity ratings plus the ratings on performance levels (systems tolerance) are to be combined mathematically with performance degradation factors in estimating the crew reliability for each mission phase.

(2) Crew workload, continuous difficult task performance, and fatigue due to duty cycle do not appear to constitute pertinent factors influencing or degrading crew performance.

(3) Five "time critical" flight phases have been identified for particular attention, not because of their difficulty but because of their importance to the successful completion of the mission.

4. Biomechanical and Environmental Stress

The items considered under this particular factor were as follows:

(1) Atmosphere.

(2) Protective equipment.

(3) Noise.

(4) Vibration.

(5) Acceleration.

(6) Radiation.

(7) Weightlessness.

The noise, vibration, and acceleration factors considered in the study were those given in Appendix A of the Statement of Work, M-WE 8020. 001 (Ref. 1). During the study, these environments were found to be satisfactory for high crew performance and could easily be provided within either the LOR or DF mode. The requirements for the internal cabin atmosphere could also be provided for either mode. Although this oxygen level has been considered a negligible factor in performance degradation in the present study, this assumption warrants reconsideration when data based on realistic simulation of crew performance at 100% oxygen levels are available.

The effects of weightlessness are also not considered as contributing to performance degradations in either mode. It is believed that, even within the confines of the restrictive DF volumes, exercise regimes could be developed to maintain muscle tone, etc.

The effects of irradiation on performance, of course, are dependent upon the amount of onboard shielding and solar activity during the period of flight. As discussed in Section VI, avoidance of doses exceeding 100 rpm at the blood-forming organs was established as a design criterion for the two systems. Doses on the order of 200 to 250 rem might be expected to produce nausea and general illness as experienced during the early prodromal phase of radiation sickness; under such circumstances some performance degradation would be likely, particularly for "time critical" tasks. With the assumption of the 100-rem limitation, however, radiation has been eliminated as a significant influence on crew performance.

Pressure suit limitations were not considered as a performance decrement factor. It was assumed that an adequate suit could be developed both to protect the crew member from his immediate environment and also to provide adequate mobility and donning characteristics. For the DF mode, a pressure suit was conceptualized which would have capability for removal of only certain portions. This would be necessary in view of the highly reduced volume of this mode. If these developments cannot be achieved, it is believed that performance decrements in the DF mode will be more severe than those estimated herein because of the severe volume reductions.

5. General Psychological Stress

One of the major factors that the general literature indicates as a probable degradation factor in skilled performance is psychological stress. The term stress, itself, cannot be considered descriptive of all the implications of this variable. Therefore, stress is defined as any external or internal stimulus or complex of stimuli which produces a change in behavior. It is common practice to consider this change in behavior as a degradation in skilled performance, abnormal emotional behavior, etc. The difficulty in determining whether a particular stimulus or a complex of stimuli is stressful is due to the variability of the emitted response. That is, there are wide intersubject variabilities as well as intrasubject variability. Further, the wide intrasubject variation would indicate that the responses to stressing agents vary as a function of time. This leads to direct consideration of adaptive behavior on the part of the subject to stressful stimuli or situations. The complexity of this problem should now be evident.

In long term space flight such as the lunar landing missions under consideration in the present study, the delineation of particular factors which would lead to psychological stress is most difficult. One may question whether the confinement environment itself is a psychological stress. It was indicated earlier that the restrictive environment of the DF mode was a possible factor in degrading performance, and that the degradation might be partially attributable to stress effects. The larger volume in the LOR mode was not considered to be stressful since a previous simulation (Ref. 6) indicated no signs of stress. The investigation of the LOR mode during this simulation not only evaluated stress from performance data but also from physiological data. During each of three simulated flights, complete urine samples were taken on all crew members every four hours with the exception of the sleep periods. Analyses of the urine for corticosteroids no variation in corticosteroid level from that which would be expected in a nonstressful situation (Refs. 18 and 19). Further, certain simple behavioral tests were employed (reaction time and time estimation) which were considered and previously utilized as sensitive stress indicators in another study (Ref. 15). The results of these tests indicated no change in performance during any of the three flights. It can be fairly well asserted from the simulator data that there appeared to be no reactivity to any stress by the crew members as measured in the study. The validity of the above statement is dependent upon the sustained adherence of simulation to actual flight. There was no physical danger or environmental condition which could produce a stress. However, there also was no motivation for the high performance that would exist during a live mission in which concern for survival, and excitement of exploration, are actual. Whether these factors (danger and high motivation) balance each other is only conjectural at present.

It should be noted that another simulation study utilizing non-test pilot personnel (Ref. 5) indicated high reactivity to the stress contained within the simulation. This would tend to indicate again the importance of individual difference in reaction to stress. The simulation using trained test pilots as crew members represented a good population sample of those considered as astronauts. This low reactivity to stress might be considered then as a trait of this population.

Returning to the DF mode, it appears reasonable to assume that the probability of reactivity to confinement stress increases as the confinement volume decreases. However, because the specific differentiation of the stress variables is extremely difficult, its import has been considered included under the general factor called restrictive volume.

It must be acknowledged that anxiety and other stress factors not related to specific mission or system considerations may affect crew performance. Such factors have been neglected in the present study, not because they are considered negligible, but because of inability to obtain adequate data to support analysis. It can at least be stated, however, that no evidence was found to suggest that performance degradation due to these additional stress factors would be significantly different between the two modes.

B. ASSUMPTIONS, CREW TASK ASSIGNMENTS, AND MATHEMATICAL CONSIDERATIONS

Based upon the discussion presented earlier in this section a number of assumptions were made. These are as follows:

(1) Performance degradation throughout the lunar mission in either mode is primarily a function of volume restriction, task difficulty, and level of performance required.

(2) The volume restriction factor includes those aspects of confinement and psychological stress which interact with it. The volume restriction factor, therefore, is a composite stress factor of all those factors related to restriction.

(3) The volume degradation factor also includes those effects upon performance caused by limited mobility, poor sanitation facilities, and poor display system scan pattern.

(4) All other factors appear to be noncontributing to performance degradation.

The approach utilized to determine the effects of the three factors on performance degradation was to mathematically relate each of these three factors. Consideration was initially given to the volume restriction factor. The effect of volume restriction has been treated as a function of time and the degree of restriction. Based upon available data, curves showing the volume restriction effects as a function of time were developed for each of three categories of tasks: systems management, switching, and control. Each crew task was put into one of these categories. Figures IV-3, IV-4 and IV-5 present the reliability of performance for each category of task as a function of time for three volumes.

The curves giving reliability as a function of volume and time were developed in accordance with certain general properties, in addition to available specific numerical data. These properties concern the initial slope (degradation rate), overall dependence on time, and interrelationships between the long term reliabilities.

Consider first the initial degradation rate of the reliability for various capsule volumes and task categories. For each fixed type of task the initial degradation rate should be a monotone nonincreasing function of capsule volume; that is, an increase in cabin volume will never cause the reliability on any one type of task to decay more rapidly at the beginning of the mission. Similarly, at a fixed volume, the initial degradation rate varies with type of task. The reliability of management tasks falls off more quickly than does that of switching, and the reliability of control tasks degrades less rapidly than either of the other two. Thus, at the beginning of a mission, the reliability will degrade because of both confinement and type of task; further, the initial degradation will be greater in capsules of smaller volume and will be greater for management tasks than for control tasks.

For a given volume and type of task, reliability is a concave function of time. That is, reliability is a monotone nonincreasing function of time for which the degradation rate is greatest initially. Skills which are acquired through training and long practice are less susceptible to environmental effects than are behaviors which require little specific training. Thus, for a given volume, management task reliabilities decay relatively quickly to a steady state value, whereas control task reliabilities endure longer, with switching task reliabilities in between those of management and control. However, the ultimate, or steady state, reliabilities for management tasks will be higher than those of control tasks, because of total forgetting or extinction of learned performance of the control tasks.

The end-of-mission reliabilities are, for each type of task, larger for larger cabin volumes. The control task reliability is most sensitive to volume; that is, an increase in cabin volume will yield a larger increase in end-of-mission control reliability than in management task reliability.

It should be noted that the three specific volumes utilized were 80 cu ft (DF) 240 cu ft (LOR CM), and 107 cu ft (LEM). The LOR mode necessitated a consideration of both 240- and 107-cu ft volumes for the respective tasks performed within each vehicle for specific phases.

With the effects of restrictive volumes on performance for each task category obtained as described above, an analysis of the different crew tasks as a function of mission phase was conducted for both modes of lunar landing. This sequential listing of crew tasks which fell into one of the three task categories is presented in Appendix A (ER 12750). Each task was further identified by the following:

(1) Number of crew members involved in performing the task.

(2) Number of job elements involved for each task.

(3) Rating of task difficulty.

[redacted]

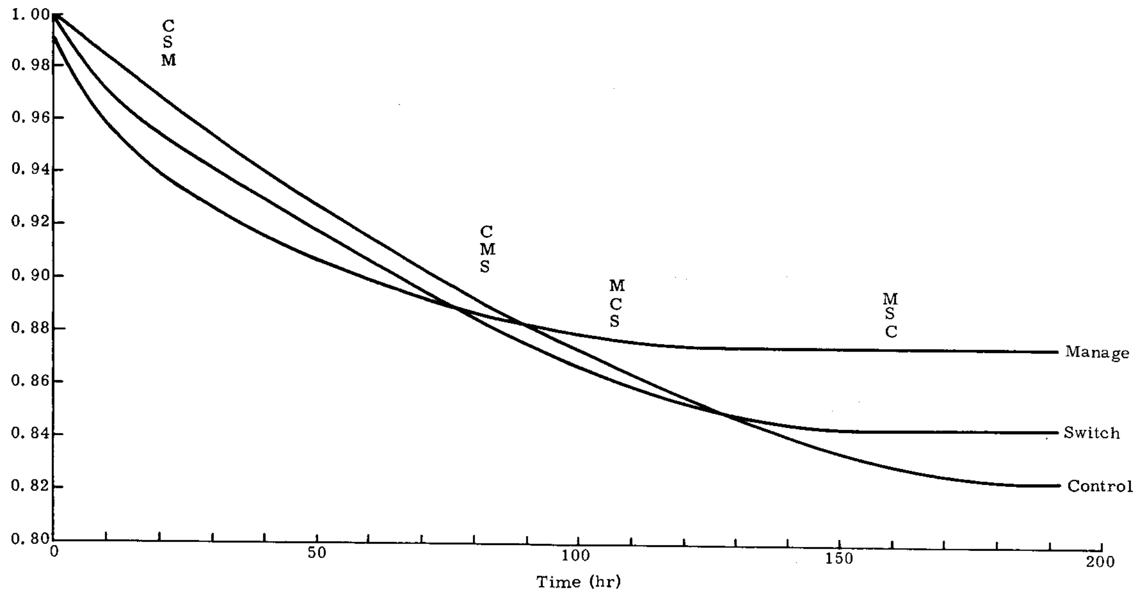


Fig. IV-3. Reliability at 80 Cubic Feet

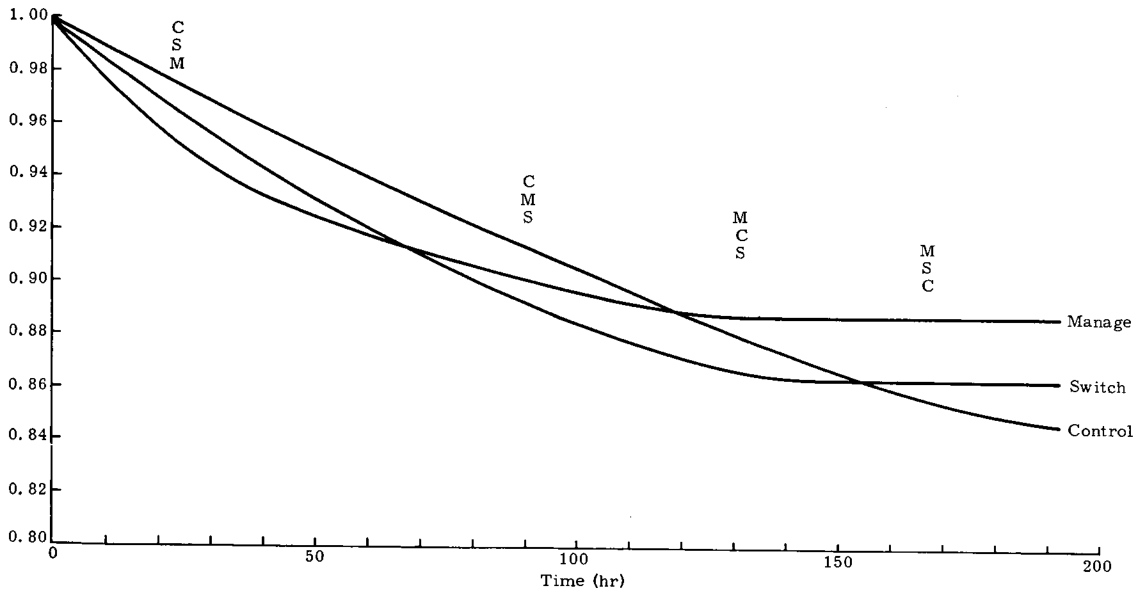


Fig. IV-4. Reliability at 107 Cubic Feet

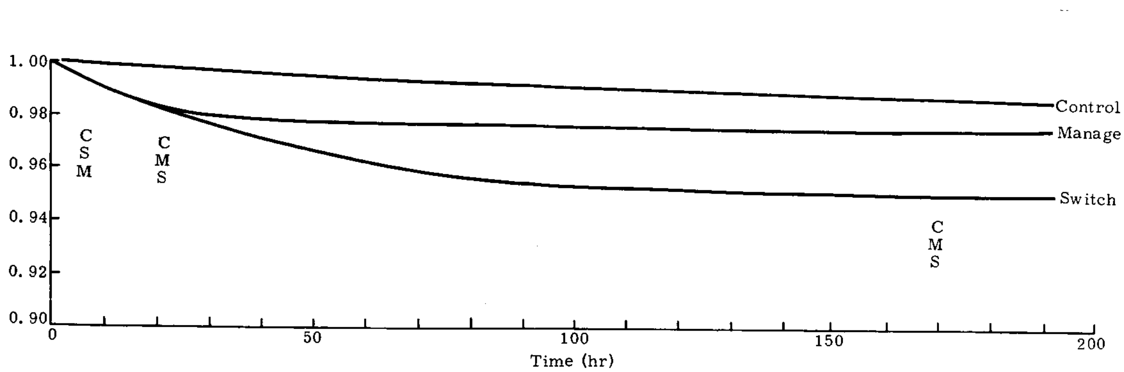


Fig. IV-5. Reliability at 240 Cubic Feet

[redacted]

(4) Rating for level of required performance.

The "number of crew members" category and the "job elements" category were discussed previously under workload. The ratings for task difficulty and level of required performance were utilized in the following manner.

In computing the average reliability by phases for each type of task, it was necessary to obtain the net reliability for each action within the phase. Thus net reliability was considered to be the product of two factors which, together, accounted for all the ways in which degradation was assumed to be able to occur. These two factors are a general environmental factor and a task-specific factor. The curves of Figs. IV-3, IV-4, and IV-5, showing reliability as a function of volume and time by types of task, give the general environmental factor. The task-specific factor considers the difficulty, or complexity, of each task, and the allowable tolerance in performing that task, with regard to overall mission completion. For each task throughout each mode, these two parameters were evaluated on a rating scale. The seven-point rating scale used for difficulty is given in Table IV-1, and the three-point rating scale for allowable tolerance in Table IV-6.

The task-specific factor is then to be related to the ratio of tolerance to difficulty. Clearly the ratio of the two rated values cannot be taken as this factor (for if it were, net reliabilities might range from $-\infty$ to $+\infty$), so that some scaling was in order. The task-specific factor is intended to be a fine correction, accounting for about $\pm$ 0.02 in net reliability of each task. Considering that the reliabilities for man are generally on the order of 0.900, the range of the task-specific factor, f, was then taken to be

$$0.980 \leq f \leq 1.020.$$

The rated values of difficulty and tolerance were then suitably mapped into this interval, as summarized in Table IV-7.

TABLE IV-7

Task-Specific Factor as a Function of Tolerance and Difficulty

	Difficulty Ratings						
Tolerance Rating	-3	-2	-1	0	+1	+2	+3
-1	1.010	1.005	1.000	0.995	0.990	0.985	0.980
0	1.015	1.010	1.005	1.000	0.995	0.990	0.985
+1	1.020	1.015	1.010	1.005	1.000	0.995	0.990

The computation of average reliabilities over each phase, by type of task, then consisted of computing the net reliability (the product of the reliability as obtained from the appropriate volume restriction curve, and the task-specific factor as obtained from Table IV-7) for each task of the given type within the given phase, and then arithmetically averaging these over the phase.

C. RESULTS

Table IV-8 presents the reliabilities for the crew functions as estimated by the methods discussed above. These data assume that the crew performs the task without verification of crew actions. In many of the tasks, however, the capability exists for verification, and a crew member may perform the task again if proper verification is not given. Crew performance reliabilities considering the verification capability were estimated as explained in the "second try" discussion in Section V. These values, given in Table IV-9, were employed where applicable in the system reliability estimation.

It should be recognized that, because of the paucity of applicable data and available techniques upon which to base these reliabilities, there is "noise" in the crew performance reliability data presented. The extent or amount of the "noise" cannot be adequately estimated. Though the procedure followed and the techniques utilized are intuitively logical, the absolute accuracy of the derived data is somewhat in doubt. Therefore, the reliability figures for crew performance should be used in a judicious manner. The manner in which these data were employed in the system reliability analysis is discussed in Section V.

Earlier in this chapter, it was indicated that there were five "time critical" tasks during the mission. Table IV-10 presents the various crew reliabilities on these time critical tasks, both without response verification and with response verification where possible.

This table indicates that there are differences between the LOR and DF modes on these time critical tasks. The greatest differences are noted in the control tasks during lunar landing and earth entry. One may ask what were the difficulty levels of these time critical tasks comparing the LOR and DF. Generally, it was found that the earth entry tasks in both modes, and the LOR lunar landing tasks, were judged as very difficult tasks (a rating of +2). The rendezvous and docking task was also judged very difficult. For lunar orbit escape, the task in the DF mode was an enabling task (switching category) which was judged of average difficulty (a rating of 0); for the LOR mode the task was a control task rated as difficult (a + 1 rating). The DF lunar landing was judged very, very difficult (a rating of +3). This was the only task in either mode to receive such a high rating. It was rated in this manner because of the lack of direct visual observation to aid in the landing. The lunar launch task for the LOR mode received a difficult rating (+1) while for the DF mode it was a switching task which was of average difficulty. It can be seen, then, that the major contribution to crew degradation was the restrictive volume, while task difficulty and performance level required played only minor roles.

The crew reliabilities may appear lower than anticipated; however, they are primarily dependent upon the expected long term effects of restrictive volumes. The lowest overall reliabilities occur in switching-type tasks. Increased automation of these tasks, particularly in the phases toward the end of the mission, would raise the overall level of performance. The control tasks, though most difficult, appear to be the least affected so that little concern should be expressed about man's abilities to perform these complex tasks.

[redacted]

TABLE IV-8

Comparison of Crew Performance Reliabilities on Three Task Categories

LOR

Phase	Control	Switch	System Management
Earth orbit coast	--	1.000	1.000
Third stage	1.000	1.000	--
LEM transfer	.994	.999	1.000
Midcourse	.992	.975	--
TL coast	.989	.999	.983
LO retro	.989	.959	--
LO coast	.989	.959	.980
LEM sep	.989	--	--
CM orbit coast	--	.955	.980
Lunar descent	.972	.948	.966
Lunar landing	.970	--	--
Lunar operations	--	--	--
Lunar launch	.923	.901	.913
Rendezvous and dock	.929	.907	.900
LO escape	.985	.947	.975
Midcourse	.983	.952	--
Transearth coast	--	.951	.980
Earth entry and landing	.980	.948	.981

Direct Flight

Phase	Control	Switch	System Management
Earth orbit	--	.984	1.000
Third stage	--	.992	--
Midcourse	--	.939	--
TL	--	.950	.938
LO retro	--	.899	.902
LO coast	--	.898	.897
Lunar descent	--	.895	.898
Lunar landing	.889	.895	--
Lunar operations	--	--	--
Lunar launch	--	.853	.873
Lunar orbit escape	--	.851	--
Midcourse	--	.846	--
Transearth	--	.826	.881
Earth entry and landing	.814	.783	.884

[redacted]

TABLE IV-9

Comparison of Crew Performance Reliability with Ability for Response Verification

LOR

Phase	Control	Switch	System Management
Earth orbit coast	--	1.000	1.000
Third stage	1.000	1.000	--
LEM transfer	.994	.999	1.000
Midcourse	.992	.999	--
Translunar coast	.989	.999	.938
LO retro	.989	.998	--
LO coast	.989	.998	.980
LEM sep	.999	--	--
CM orbit coast	--	.997	.980
Lunar descent	.972	.989	.966
Lunar landing	.999	--	--
Lunar operations	--	--	--
Lunar launch	.923	.982	.913
Rendezvous and dock	.988	.983	.900
LO escape	.985	.996	.975
Midcourse	.983	.998	--
Transearth coast	--	.997	.980
Earth entry landing	.980	.996	.981

Direct Flight

Phase	Control	Switch	System Management
Earth orbit	--	1.000	1.000
Third stage	--	1.000	--
Midcourse	--	.996	--
Translunar	--	.995	.938
LO retro	--	.991	.902
LO coast	--	.980	.897
Lunar descent	--	.979	.898
Lunar landing	.889	.989	--
Lunar operations	--	--	--
Lunar launch	--	.962	.873
LO escape	--	.977	--
Midcourse	--	.976	--
Transearth	--	.953	.881
Earth entry and landing	.814	.933	.884

[redacted]

TABLE IV-10
Crew Reliabilities for Time-Critical Tasks

Phase	LOR			Direct Flight		
	Control	Switch	Management	Control	Switch	Management
Lunar landing	.970 (.999)	--	--	.889	.895 (.989)	--
Lunar launch	.923	.901 (.982)	.913	--	.853 (.962)	.873
Rendezvous and dock	.929 (.988)	.907 (.983)	.900	--	--	--
LO escape	.985	.947 (.996)	.975	--	.851 (.977)	--
Earth entry and landing	.980	.948 (.996)	.981	.814	.783 (.933)	.884

NOTE: Figures in parentheses include response verification.

[redacted]

D. EMERGENCY SITUATIONS

The previously mentioned results applied to a normal flight. It was, however, considered important to attempt to determine the effects on crew performance from various types of malfunction of abort situations. Due to time limitations not all the possible situations could be studied; therefore a sample of six emergency situations was selected for the DF mode and seven for the LOR. The situations utilized, described in Section III, can be summarized as follows:

(1) Meteoroid penetration of the pressure cabin.

(2) Landing engine failure.

(3) Partial electrical power failure.

(4) One crew member disabled on lunar surface.

(5) Partial failure of the environmental control system.

(6) Partial guidance system failure.

(7) (LOR only) LEM propulsion failure in lunar parking orbit.

An analysis of crew tasks to be performed during each of these emergency situations was conducted and brief task analyses are presented in Appendix B (ER 12750). The results indicate that with the exception of the man disabled condition and the LEM propulsion failure in lunar parking orbit all tasks are well within the performance range and most tasks are not very difficult. Further simulation data has indicated with some similar malfunctions that crew performance during these emergency conditions is extremely high (Ref. 6). Therefore we must assume that all conditions presented with the exception of the two listed above do not add significantly to any degradation already present.

The man disabled during lunar landing presents a significant degradation problem for the DF mode, particularly in consideration of workload. The remaining crew member would be required to perform all tasks by himself and rely exclusively on earth control and automatic systems. The LOR workload level also changes but not as drastically. However, an analogous situation in the LOR mode to the above mentioned DF condition would be in the loss of the LEM on the lunar surface. The remaining crew member in the LOR command module would be required to return the vehicle to earth alone. This expected degradation would probably be greater in this LOR condition than in DF condition already mentioned because of less automation in the LOR Command Module, and the generally greater task load.

The LEM propulsion failure in lunar parking orbit is another condition which requires a great deal of effort from the single crew member in the LOR Command Module. Since this situation would require the single crew member in the LOR Command Module to perform the rendezvous with the "stalled" LEM, a number of critical questions appear. First, are the handling qualities of the LOR Command Module satisfactory for such a rendezvous task? Second, can a single crew member perform the rendezvous with the complex display and control system of the LOR Command Module? Both of these questions appear to be unanswerable within the scope of the present study and therefore no estimates of crew degradation due to this malfunction are given. It would, however, appear to present a major workload problem for the single crew member in the LOR Command Module.

Both the man-disabled and LEM propulsion failure present abort or malfunction conditions where man's performance may be limited. Actual assignment of reliability figures as to his performance ability under these circumstances would require considerable analytical and experimental work.

V. SYSTEM RELIABILITY AND SAFETY

The objective of the reliability and safety analyses was to determine the effects of man on the successful accomplishment of the Apollo mission for the LOR and DF modes.

Reliability and safety models upon which the analyses were based initially postulated completely mechanized, automatically operated onboard systems as defined in Ref. 1. Using the LOR and DF configurations described in Sections II and III, man was placed into the systems loop--in some cases completely displacing automated equipment or functions, in some acting in a systems monitoring and verifying capacity, and in others performing switching operations required for maintenance of equipment reliability. His effect on mission success and safety was determined and included in tables following the format and model of the OS (Ref. 1) tables.

A. ASSUMPTIONS

In order to perform an adequate analysis within the specified requirements, a number of assumptions had to be made. These assumptions, applying equally to both the DF and LOR, constitute the ground rules upon which the study was conducted. They were as follows:

(1) The basis for study, the definition of general mission mathematical models, and the format for study results were the Ref. 1 tables (revised) and the "Bases for Reliability Estimates Included in Statement of Work" provided in Ref. 3. The chief revision affecting these models was the necessary incorporation of pump-fed LOX-hydrogen in place of earth storables in the DF configuration.

(2) Environmental control and power systems were included in the DF and LOR configurations as vital. Based upon equipment reliability estimates, their incorporation did not alter the phase reliabilities of the OS tables.

(3) Based upon the OS system reliability estimates, communications were not included as a part of mission reliability and safety. It was therefore assumed that their failure would in no case cause an abort.

(4) Consistent with the OS estimates, the reliability of equipment was not considered to degrade during nonoperating or standby periods.

(5) The probability of no critical meteoroid penetrations during each mission phase was applied to the man-machine phase reliability of each configuration by means of the product rule. The meteoroid model employed was that of the LEM RFP. Because of uncertainty as to the specific radiation shielding to be provided in the actual LEM, the probability of not exceeding a specified integrated dose was not applied directly to the total mission probability of success, but is discussed separately in Section VI.

(6) DF and LOR configurations have equal safety, fuel, and performance margins throughout the mission.

(7) DF and LOR onboard systems were of the same configuration, except for the main propulsion systems.

(8) Because of the necessity of computing equipment reliability at the subsystem and sometimes component levels, eight decimal place values were used throughout the analysis instead of six decimal place values as given by NASA in Ref. 3 for system level values of reliability. Crew performance reliabilities, estimated to three decimal places, were assumed to be mean values, thus permitting the use of uniform and more readily accomplished computations.

(9) In the establishment of man-machine reliability models, the crew performance reliability estimates were considered to cover preclusion of the man switching a properly operating unit to a standby unit.

B. RELIABILITY AND SAFETY ESTIMATION AND RESULTS

The final results of the reliability and safety analysis are presented in Tables V-1 and V-2, in the mission phase format used in Ref. 1. Supporting data and intermediate steps are shown in Tables V-3 through V-9. The models shown in Tables V-3 and V-4 illustrate the steps employed in calculating the final values; Tables V-5 and V-6 show the major system and subsystem estimates utilized in obtaining the phase reliabilities; and Tables V-7, V-8 and V-9 illustrate the incorporation of meteoroid penetration hazards into the reliability estimation.

Each table has four groups of values: A, B, C and D. In each case, A shows the reliability and safety for a fully automatic mechanized system (i.e., the OS estimates modified as indicated in the above assumptions); B shows reliability and safety for a fully automatic mechanized system using a perfect man-machine backup combination; C and D show a partially automatic system with a nonredundant guidance system incorporating emergency backup navigation equipment, C assuming 100% crew performance, and D utilizing crew performance reliability estimates determined as explained in Section IV. Groups C and D, then, represent the LOR system relistically postulated on the basis of the present Apollo/LEM development approach, and Group D represents a conceptually similar hypothetical DF system. Groups A and B represent more idealized systems somewhat less compatible with weight and state-of-the-art limitations.

1. Group A--Fully Automatic System

The Group A systems were defined with varying degrees of redundancy as follows:

(1) Fully redundant, automatic switching of malfunctioning equipment, programmed enable as applicable.

(a) Power (electrical)--Martin proposed.

(b) Environmental control--Martin proposed.

(c) Attitude control (including roll control)--LEM RFP and Martin proposed.

(d) Flight control system--LEM RFP and Martin proposed.

(e) Electronics and guidance--LEM RFP.

(2) Partially redundant, automatic switching of failed components, programmed enable as applicable.

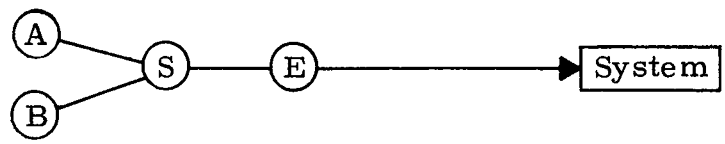
(a) Main propulsion including fuel and oxidizer systems, dual burn control (fuel and oxidizer), throttling control, hydraulic controls, propellant utilization, engines.

(b) Airframe and separation.

(c) Instruments.

The basic reliability models used in synthesizing Group A subsystem reliabilities are indicated below:

For redundant systems and subsystems:



System reliability $= R_E \left[R_A R_{S_1} + R_A Q_{S_1} R_B + Q_A R_B R_{S_1} \right]$

where:

R_A = reliability of equipment A.

R_B = reliability of equipment B.

R_{S_1} = probability that switch S will not shut off a good item of equipment (one-time use).

R_{S_2} = probability that switch S will shut off a bad item of equipment (one-time use).

R_E = reliability of programmed enabling device.

Q_i = failure of the ith system (i.e., $Q_i = 1 - R_i$).

For nonredundant systems,

System reliability $= R_A R_E$

By means of these basic models, equipment, switching, and enabling reliabilities were established for subsequent use in the analysis as follows:

(1) Equipment reliabilities (R_A, R_B...) were obtained from Martin LEM and Apollo analyses.

(2) It was assumed that switching reliability (S) was equal to programmed enabling reliability (E). Further, it was assumed that $R_{S_1} = R_{S_2}$, i.e., it was equally probable that the switch would not shut off a good item of equipment as it was that it would switch off a bad item of equipment.

(3) System reliability values used were those given in Tables V-5 and V-6 (Group A).

2. Group B--Fully Automatic System with Perfect (100% Crew Performance) Man-Machine Backup

These reliabilities are derived phase values using the identical equipments as defined in Group A with a fully capable man functioning in the equipment loop (i.e., 100% probability of accomplishing task).

The basic mathematical models used were as follows:

$$\text{System reliability} = R_E + Q_E R_M \quad R_A R_{S_1} + R_A Q_{S_1} R_M + Q_A R_B R_{S_2} + Q_A R_B Q_{S_2} R_M$$

where

R_A = reliability of equipment A.

R_B = reliability of equipment B.

R_{S_1} = probability that switch S will not shut off a good item of equipment (one-time use).

R_{S_2} = probability that switch S will shut off a bad item of equipment (one-time use).

R_M = probability that man will override malfunctioning of switch, in either S_1 or S_2 mode, and enabling device E.

R_E = reliability of programmed enabling device.

Q_i = failure of the ith system (i.e., $Q_i = 1 - R_i$).

The Group B values were obtained by using $R_M = 1.000$ and the values of equipment, switching, and enabling reliability and probability of failure derived for Group A.

This "ideal" system is inconsistent in some areas with weight and state-of-the-art limitations. The data are included to indicate the order of reliability improvement achievable by adding man in the most ideal manner to an optimum system. Since this system does not represent the actual approach envisioned for either mode, Group B combinations were not re-estimated for the degraded crew performance.

3. Group C--Partially Automatic System with Recommended Man-Machine Relationship (100% Crew Performance)

In this group, a number of changes were made to onboard systems and to the tasks and functions allocated to the man. The automatic landing system was eliminated, and simplified backup guidance equipment was employed, rather than a completely redundant guidance system added. Additionally, tasks assigned to the man, and automatically programmed enable functions, were modified to conform with the task assignments shown in Figs. III-5 and III-6. System reliabilities were estimated from the basic mathematical models used in Group B, using $R_M = 1.000$.

4. Group D--Group C Modified to Include Estimated Crew Performance Reliabilities

Group D values incorporate the equipment and operating methods of Group C, but used the estimated crew performance reliabilities in place of the arbitrary $R_M = 1.000$.

Using the crew performance reliabilities determined by analysis (Table IV-9) and the method of operation defined in Figs. III-5 and III-6, probabilities of man successfully accomplishing assigned tasks and functions were determined as follows:

(1) Control functions only, no verification, no backup, no second chance R_C-- Columns 1 and 4 of Table IV-9.

(2) Control functions, verifications, correction capability (Columns 2 and 5).

Probability of successfully completing control function =

$$R_{C_1} R_V + R_{C_1} Q_V + Q_{C_1} R_V R_{C_2}.$$

where

R_{C_1} = probability of completing control function within required limits.

R_V = probability of properly verifying control action.

Q_V = probability of not verifying control action.

Q_{C_1} = probability of not completing control function on first try.

R_{C_2} = probability of completing control function on second try.

(3) Enable switch functions, verification, correction capability (Columns 3 and 6).

Probability of successfully completing enabling function =

$$R_{E_1} R_V + R_{E_1} Q_V + Q_{E_1} R_V R_{E_2}$$

where

R_{E_1} = probability of completing enable (switching) function within required limits.

R_V = probability of properly verifying enabling (switching) function.

Q_V = probability of not verifying enabling (switching) function.

Q_{E_1} = probability of not completing control function on first try.

R_{E_2} = probability of completing control function on second try.

It will be noted in items (2) and (3) above that in all cases where multiple attempts were feasible to control, enable, or switch, man was given only a single correcting second try. It is obvious of course, that there will be numerous special occasions when man will have more than a second try, each succeeding attempt improving the probability of success ($R \rightarrow 1.000$ as a limit.) However, one second try only was assumed in the study because:

(1) An infinite number of tries was obviously impossible (i.e., $R \rightarrow 1.000$) and the exact number of tries could not be determined. To eliminate possible bias to LEM or DF, one re-try only was assumed for this study.

(2) Sufficient data were not available to allow more than one re-try since the probability of successfully accomplishing succeeding re-tries might not be constant. Substantially the same mistake might be made over and over again with obviously doubtful improvement in probability of success no matter how many re-tries.

C. METEOROIDS

Meteoroid penetration hazards for the two study configurations were estimated as follows:

(1) Penetration equation of Ref. 20 modified for thin targets was employed.

(2) Bumper effectivity was assumed as three times the effectivity of an equivalent single skin.

(3) Mutual shielding of components was taken into account.

(4) Earth shielding and lunar shielding during earth orbit, lunar orbit and lunar landing/takeoff/exploration were assumed to reduce the free space meteoroids hazard 50%.

(5) It was assumed that the penetration of any equipment or crew compartments would not prevent abort (no immediate catastrophic hazard); penetration of the crew comparments would not cause destruction of any equipment mounted inside; and crew members would not be hit by meteoroids when inside their compartments or when on the lunar surface.

(6) Meteoroid densities were assumed to be 3.5 gm/cc.

Tables V-7, V-8 and V-9 show the results of the analysis for the DF, the LOR CM, and the LEM. It will be noted that the crew compartment of the LEM contributes approximately one-third the total meteoroid hazard to LOR. In the DF case however, the LOX-hydrogen tanks in both the landing module and service module contribute more than 95% of the meteoroid hazard, and the CM meteoroid hazard is less than 1% of the total. Additionally, the probability of no penetration is approximately 98.3% for the LOR mission and 95.5% for the DF mission.

D. DISCUSSION OF RESULTS

The key results - the "answers" sought in the study - may be summarized as follows:

	LOR		DF	
	Mission Success Probability	Crew Safety	Mission Success Probability	Crew Safety
A. "Ideal" fully automatic system	0.4278	0.9078	0.3586	0.8568
B. "Ideal" fully automatic system with manual backup (100% crew performance)	0.4655	0.9194	0.3885	0.8678
C. Proposed man-machine system with 100% crew performance	0.4618	0.9146	0.3855	0.8635
D. Proposed man-machine system with estimated crew performance reliability	0.4201	0.9055	0.3182	0.8450

No direct comparison can be made between the figures for the "ideal" A and B systems and those for the proposed C and D systems, since in addition to the assumed full automation the "ideal" cases are assumed to have fully redundant guidance systems. If one were to consider a hybrid system representing the proposed C system with automatic landing and without fully automatic guidance redundancy (i.e., the C system with man removed from the loop), the estimated reliabilities would fall well below any of values shown above, running on the order of 0.3687 for LOR and 0.2910 for DF.

Comparison of the C and D figures indicates that for the proposed man-machine systems, the incorporation of estimated crew performance reliability results in degradation of mission success probability by 9% for the LOR and 17.5% for the DF. The crew safety figures exhibit differences of approximately the same order (10% versus 21.4%). An appreciable reduction in the DF reliability degradation might be realized by greater automation of functions, particularly in the latter phases of the mission where the degradation in crew performance is most apparent, as discussed in Section IV. For the configurations utilized in the present study, however, the LOR system is inherently more reliable than the DF system, primarily because of the propulsion differences.

These results neglect the possibly important aspect of onboard maintenance which, as indicated in Section VII, would tend to suggest a significant advantage for the LOR in terms of potential beneficial crew participation.

Although relative to the "ideal" A and B systems the proposed C and D systems would be expected to be less reliable because of the necessary elimination of certain significant equipment redundancy, the levels of estimated reliability are of the same magnitude. This would indicate that the crew, even with degraded performance, has in fact contributed significantly to mission success probability. The benefits of crew participation, however, can only be realized if careful attention is given to establishment of the proper man-machine combination. For example, system reliabilities estimated early in the study on the basis of preliminary task assignment definitions showed that degradations due to estimated crew performance reliability were approximately twice as great as those shown in the final results. With further refinement of the relationships, it is believed that improvement in reliability over that shown in the present study results could be achieved. Such refinement, however, should be reserved for the actual system to be developed.

The results of the present analysis point up several indications which should be useful in establishing the final man-machine relationship. For instance, man has a unique capability of making successive attempts at, or corrections to, enabling and control tasks. Systems should be anticipated to take advantage of this capability and to provide adequate verification opportunity, reminders, backup programmed enabling, etc. With such provisions, which can be kept quite simple, the combination of man and machine can be significantly more reliable than either man alone or more sophisticated automatic systems.

The validity of the present study rests heavily, of course, on the validity of the crew performance reliability estimation. As indicated in Section IV, the uncertainties attached to these data warrant continued serious effort to obtain further analytical and experimental verification of the crew reliability estimates, not only for the lunar missions but also for planetary missions of longer time durations. Insofar as possible, data should be obtained from realistic simulation of missions and tasks using subjects representative of astronaut crews.

[redacted]

TABLE V-1
C-5 LOR Estimated Reliability and Safety Model

Step	Estimated Reliability R	Probability of Reaching Step P	Probability of Abort Q	Abort Mode A	Abort System Reliability RA	Abort System Unreliability QA	Abort Safety Failure Probability: CM & LEM Lost S	Abort Safety Failure Probability: LEM Only Lost T	Abort Success Probability For 2 Men After Lunar Landing U
1. First stage (no engine out)	R_1	1.000	$1-R_1$	Tower +20	$R_{tower}\ R_{20}$	$1-RA_1$	$P_1\ Q_1\ QA_1$	$P_1\ Q_1\ QA_1$	--
2. Second stage (no engine out)	R_2	$P_1\ R_1$	$1-R_2$	SM-A+20	$R_{SM-A}\ R_{20}$	$1-RA_2$	$P_2\ Q_2\ QA_2$	$P_2\ Q_2\ QA_2$	--
3. Earth orbit coast	R_3	$P_1\ R_1\ R_2$	$1-R_3$	SM-A+20	$R_{SM-A}\ R_{20}$	$1-RA_3$	$P_3\ Q_3\ QA_3$	$P_3\ Q_3\ QA_3$	--
4. Third stage (2 burns)	R_4	$P_1\ R_1\ R_2\ R_3$	$1-R_4$	SM-A+18+19+20	$R_{SM-A}\ R_{18}\ R_{19}\ R_{20}$	$1-RA_4$	$P_4\ Q_4\ QA_4$	$P_4\ Q_4\ QA_4$	--
5. LEM transfer	R_5	$P_1\ R_1\ R_2\ R_3\ R_4$	$1-R_5$	SM-A+18+19+20	$R_{SM-A}\ R_{18}\ R_{19}\ R_{20}$	$1-RA_5$	$P_5\ Q_5\ QA_5$	$P_5\ Q_5\ QA_5$	--
6. Midcourse	R_6	$P_1\ \pi\ (R_1$ through $R_5)$	$1-R_6$	SM-A+18+19+20	$R_{SM-A}\ R_{18}\ R_{19}\ R_{20}$	$1-RA_6$	$P_6\ Q_6\ QA_6$	$P_6\ Q_6\ QA_6$	--
7. Translunar coast	R_7	$P_1\ \pi\ (R_1$ through $R_6)$	$1-R_7$	SM-A+18+19+20	$R_{SM-A}\ R_{18}\ R_{19}\ R_{20}$	$1-RA_7$	$P_7\ Q_7\ QA_7$	$P_7\ Q_7\ QA_7$	--
8. Lunar orbit retro	R_8	$P_1\ \pi\ (R_1$ through $R_7)$	$1-R_8$	SM-A+18+19+20	$R_{SM-A}\ R_{18}\ R_{19}\ R_{20}$	$1-RA_8$	$P_8\ Q_8\ QA_8$	$P_8\ Q_8\ QA_8$	--
9. Lunar orbit coast	R_9	$P_1\ \pi\ (R_1$ through $R_8)$	$1-R_9$	SM-A+18+19+20	$R_{SM-A}\ R_{18}\ R_{19}\ R_{20}$	$1-RA_9$	$P_9\ Q_9\ QA_9$	$P_9\ Q_9\ QA_9$	--
10. LEM separation	R_{10}	$P_1\ \pi\ (R_1$ through $R_9)$	$1-R_{10}$	Dock +17+18+19+20	$R_{dock} + R_{17}\ R_{18}\ R_{19}\ R_{20}$	$1-RA_{10}$	$P_{10}\ Q_{10}\ QA_{10}$	$P_{10}\ Q_{10}\ QA_{10}$	--
11. CM orbit coast	R_{11}	$P_1\ \pi\ (R_1$ through $R_{10})$	$1-R_{11}$	15+16+17+18+19+20	$R_{15}\ (R_{16}+R_{16A}\ Q_{16})\ R_{17}\ R_{18}\ R_{19}\ R_{20}$	$1-RA_{11}$	$P_{11}\ Q_{11}\ QA_{11}$	$P_{11}\ Q_{11}\ [1-R_{15}\ (R_{16}+R_{16A}\ Q_{16})]$	$P_{11}\ Q_{11}\ RA_{11}$
12. Descent to moon	R_{12}	$P_1\ \pi\ (R_1$ through $R_{11})$	$1-R_{12}$	15+16+17+18+19+20	$R_{15}\ (R_{16}+R_{16A}\ Q_{16})\ R_{17}\ R_{18}\ R_{19}\ R_{20}$	$1-RA_{12}$	$P_{12}\ Q_{12}\ QA_{12}$	$P_{12}\ Q_{12}\ [1-R_{15}\ (R_{16}+R_{16A}\ Q_{16})]$	--
13. Landing on moon	R_{13}	$P_1\ \pi\ (R_1$ through $R_{12})$	$1-R_{13}$	15+16+17+18+19+20	$R_{15}\ (R_{16}+R_{16A}\ Q_{16})\ R_{17}\ R_{18}\ R_{19}\ R_{20}$	$1-RA_{13}$	$P_{13}\ Q_{13}\ QA_{13}$	$P_{13}\ Q_{13}\ [1-R_{15}\ (R_{16}+R_{16A}\ Q_{16})]$	--
14. Lunar operations	R_{14}	$P_1\ \pi\ (R_1$ through $R_{13})$	$1-R_{14}$	15+16+17+18+19+20	$R_{15}\ (R_{16}+R_{16A}\ Q_{16})\ R_{17}\ R_{18}\ R_{19}\ R_{20}$	$1-RA_{14}$	$P_{14}\ Q_{14}\ QA_{14}$	$P_{14}\ Q_{14}\ [1-R_{15}\ (R_{16}+R_{16A}\ Q_{16})]$	$P_{14}\ Q_{14}\ RA_{14}$
15. Lunar launch	R_{15}	$P_1\ \pi\ (R_1$ through $R_{14})$	$1-R_{15}$	None	0.0000	1.0000	$P_{15}\ Q_{15}\ QA_{15}$	$P_{15}\ Q_{15}\ QA_{15}$	$P_{15}\ Q_{15}\ RA_{15}$
16. Lunar rendezvous and dock	R_{16} R_{16A}	$P_1\ \pi\ (R_1$ through $R_{15})$	$1-R_{16}$	16A+17+18+19+20	$R_{16A}\ R_{17}\ R_{18}\ R_{19}\ R_{20}$	$1-RA_{16}$	$P_{16}\ Q_{16}\ QA_{16}$	$P_{16}\ Q_{16}\ QA_{16}$	$P_{16}\ Q_{16}\ RA_{16}$
17. Lunar orbit escape	R_{17}	$P_1\ \pi\ (R_1$ through $R_{16})$	$1-R_{17}$	None	0.0000	1.0000	$P_{17}\ Q_{17}\ QA_{17}$	$P_{17}\ Q_{17}\ QA_{17}$	$P_{17}\ Q_{17}\ RA_{17}$
18. Midcourse	R_{18}	$P_1\ \pi\ (R_1$ through $R_{17})$	$1-R_{18}$	None	0.0000	1.0000	$P_{18}\ Q_{18}\ QA_{18}$	$P_{18}\ Q_{18}\ QA_{18}$	$P_{18}\ Q_{18}\ RA_{18}$
19. Transearth coast	R_{19}	$P_1\ \pi\ (R_1$ through $R_{18})$	$1-R_{19}$	CM A/C+20	$R_{CM\ A/C}\ R_{20}$	$1-RA_{19}$	$P_{19}\ Q_{19}\ QA_{19}$	$P_{19}\ Q_{19}\ QA_{19}$	$P_{19}\ Q_{19}\ RA_{19}$
20. Earth entry and landing	R_{20}	$P_1\ \pi\ (R_1$ through $R_{19})$	$1-R_{20}$	None	0.0000	1.0000	$P_{20}\ Q_{20}\ QA_{20}$	$P_{20}\ Q_{20}\ QA_{20}$	$P_{20}\ Q_{20}\ RA_{20}$
Nominal mission probability	$P_1\ \pi\ (R_1$ through $R_{20})$								
Abort success probability	$\sum_{j=1}^{20} U_j$						Crew safety $= 1 - \sum_{j=1}^{20} S_j$ for 3 men	$1 - \sum_{j=1}^{20} T_j$	$\sum_{j=1}^{20} U_j$
Mission success probability	$P_1\ \pi\ (R_1$ through $R_{20}) + \sum U$								

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TABLE V-2

C-5 DF Reliability and Safety

	Step	Estimated Reliability R	Probability of Reaching Step P	Probability of Abort Q	Abort Mode Steps A	Abort System Reliability RA	Abort System Unreliability QA	Abort Safety Failure Probability S	Abort System Probability After Lunar Landing U
1	First stage (no engine out)	R_1	1.000	$1 - R_1$	(.999) tower + 16	$R_{tower} R_{16}$	$1 - RA_1$	$P_1 Q_1 QA_1$	
2	Second stage (no engine out)	R_2	$P_1 R_1$	$1 - R_2$	(.95) SM + 16	$R_{SM} R_{16}$	$1 - RA_2$	$P_2 Q_2 QA_2$	
3	Earth orbit coast	R_3	$P_1 R_1 R_2$	$1 - R_3$	SM + 16	$R_{SM} R_{16}$	$1 - RA_3$	$P_3 Q_3 QA_3$	
4	Third stage (two burns)	R_4	$P_1 R_1 R_2 R_3$	$1 - R_4$	SM + 14 + 15 + 16	$R_{SM} R_{14} R_{15} R_{16}$	$1 - RA_4$	$P_4 Q_4 QA_4$	
5	Midcourse	R_5	$P_1 R_1 R_2 R_3 R_4$	$1 - R_5$	SM + 14 + 15 + 16	$R_{SM} R_{14} R_{15} R_{16}$	$1 - RA_5$	$P_5 Q_5 QA_5$	
6	Translunar coast	R_6	$P_1 \pi (R_1$ through $R_5)$	$1 - R_6$	SM + 14 + 15 + 16	$R_{SM} R_{14} R_{15} R_{16}$	$1 - RA_6$	$P_6 Q_6 QA_6$	
7	Lunar orbit retro	R_7	$P_1 \pi (R_1$ through $R_6)$	$1 - R_7$	SM + 14 + 15 + 16	$R_{SM} R_{14} R_{15} R_{16}$	$1 - RA_7$	$P_7 Q_7 QA_7$	
8	Lunar orbit coast	R_8	$P_1 \pi (R_1$ through $R_7)$	$1 - R_8$	SM + 14 + 15 + 16	$R_{SM} R_{14} R_{15} R_{16}$	$1 - RA_8$	$P_8 Q_8 QA_8$	
9	Descent to moon	R_9	$P_1 \pi (R_1$ through $R_8)$	$1 - R_9$	12 + 13 + 14 + 15 + 16	$R_{12} R_{13} R_{14} R_{15} R_{16}$	$1 - RA_9$	$P_9 Q_9 QA_9$	
10	Landing on moon	R_{10}	$P_1 \pi (R_1$ through $R_9)$	$1 - R_{10}$	12 + 13 + 14 + 15 + 16	$R_{12} R_{13} R_{14} R_{15} R_{16}$	$1 - RA_{10}$	$P_{10} Q_{10} QA_{10}$	
11	Lunar operations	R_{11}	$P_1 \pi (R_1$ through $R_{10})$	$1 - R_{11}$	12 + 13 + 14 + 15 + 16	$R_{12} R_{13} R_{14} R_{15} R_{16}$	$1 - RA_{11}$	$P_{11} Q_{11} QA_{11}$	$P_{11} Q_{11} RA_{11}$
12	Lunar launch	R_{12}	$P_1 \pi (R_1$ through $R_{11})$	$1 - R_{12}$	None	.0000	1.0000	$P_{12} Q_{12} QA_{12}$	$P_{12} Q_{12} RA_{12}$
13	Lunar orbit escape	R_{13}	$P_1 \pi (R_1$ through $R_{12})$	$1 - R_{13}$	None	.0000	1.0000	$P_{13} Q_{13} QA_{13}$	$P_{13} Q_{13} RA_{13}$
14	Midcourse	R_{14}	$P_1 \pi (R_1$ through $R_{13})$	$1 - R_{14}$	None	.0000	1.0000	$P_{14} Q_{14} QA_{14}$	$P_{14} Q_{14} RA_{14}$
15	Transearth coast	R_{15}	$P_1 \pi (R_1$ through $R_{14})$	$1 - R_{15}$	CM A/C + 16	R_{CM} A/C R_{16}	$1 - RA_{15}$	$P_{15} Q_{15} QA_{15}$	$P_{15} Q_{15} RA_{15}$
16	Earth entry and landing	R_{16}	$P_1 \pi (R_1$ through $R_{15})$	$1 - R_{16}$	None	.0000	1.0000	$P_{16} Q_{16} QA_{16}$	$P_{16} Q_{16} RA_{16}$

Nominal mission probability $P_1 \pi (R_1$ through $R_{16})$

Crew safety $= 1 - \sum_{j=1}^{20} S_j$ $\qquad \sum_{j=1}^{16} U_j$

Abort success probability $\sum_{j=1}^{20} U_j$

Mission success probability $P_1 \pi (R_1$ through $R_{16}) + \sum_{j=1}^{16} U_j$

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TABLE V-3

DF Estimated Reliability and Crew Safety (Equipment + Meteoroid Hazard)

		Steps	Estimated Reliability	Probability of Reaching Step	Abort Probability	Abort Mode Step	Abort System Reliability	Abort System Unreliability	Abort Safety Failure Probability	Abort Success Probability After Lunar Landing
1	A		.8778	1.0000	.1222		.9890	.0110	.0013	
	B	First-stage boost (no engine out)	.8778	1.0000	.1222	Tower + 16	.9971	.0029	.0004	
	C		.8778	1.0000	.1222		.9930	.0070	.0009	
	D		.8778	1.0000	.1222		.9918	.0082	.0010	
2	A		.8302	.8778	.1698		.9405	.0595	.0089	
	B	Second-stage boost (no engine out)	.8302	.8778	.1698	SM + 16	.9482	.0518	.0077	
	C		.8302	.8778	.1698		.9442	.0557	.0083	
	D		.8302	.8778	.1698		.9431	.0569	.0085	
3	A		.9988	.7287	.0012		.9405	.0595	.0001	
	B	Earth orbit coast	.9997	.7287	.0003	SM + 16	.9481	.0519	.0000	
	C		.9997	.7287	.0003		.9442	.0558	.0000	
	D		.9996	.7287	.0004		.9431	.0569	.0000	
4	A		.8644	.7279	.1356		.8390	.1610	.0159	
	B	Third stage (2 burns)	.8644	.7285	.1356		.8481	.1519	.0150	
	C		.8644	.7285	.1356	SM + 14 + 15 + 16	.8431	.1569	.0155	
	D		.8643	.7285	.1357		.8412	.1588	.0157	
5	A		.9088	.6292	.0912		.8390	.1610	.0092	
	B	Midcourse	.9104	.6297	.0896	SM + 14 + 15 + 16	.8481	.1519	.0086	
	C		.9104	.6297	.0896		.8431	.1569	.0089	
	D		.9089	.6296	.0911		.8412	.1588	.0091	
6	A		.9803	.5718	.0197		.8390	.1610	.0018	
	B	Translunar coast	.9811	.5733	.0189		.8481	.1519	.0016	
	C		.9794	.5733	.0206	SM + 14 + 15 + 16	.8431	.1569	.0019	
	D		.9793	.5723	.0207		.8412	.1588	.0019	
7	A		.9500	.5605	.0500		.8390	.1610	.0045	
	B	Lunar órbit retro	.9528	.5625	.0472	SM + 14 + 15 + 16	.8481	.1519	.0040	
	C		.9524	.5615	.0476		.8431	.1569	.0041	
	D		.9523	.5604	.0477		.8412	.1588	.0042	
8	A		.9984	.5325	.0015		.8390	.1610	.0001	
	B	Lunar orbit coast	.9993	.5360	.0007	SM + 14 + 15 + 16	.8481	.1519	.0000	
	C		.9992	.5347	.0008		.8431	.1569	.0000	
	D		.9787	.5337	.0213		.8412	.1588	.0015	
9	A		.9500	.5317	.0500		.7971	.2029	.0053	
	B	Descent to moon	.9528	.5354	.0472	12 + 13 + 14 + 15 + 16	.8104	.1896	.0047	
	C		.9524	.5343	.0476		.8049	.1951	.0049	
	D		.9511	.5224	.0489		.7720	.2280	.0058	
10	A		.8745	.5051	.1255		.7971	.2029	.0129	
	B	Land on moon	.9231	.5103	.0769	12 + 13 + 14 + 15 + 16	.8104	.1896	.0074	
	C		.9231	.5089	.0769		.8049	.1951	.0076	
	D		.8116	.4968	.1884		.7720	.2280	.0213	
11	A		.9826	.4417	.0174		.7971	.2029	.0016	.0061
	B	Lunar operations	.9924	.4710	.0076	12 + 13 + 14 + 15 + 16	.8104	.1896	.0007	.0029
	C		.9917	.4697	.0083		.8049	.1951	.0008	.0032
	D		.9917	.4032	.0083		.7720	.2280	.0008	.0031
12	A		.9500	.4340	.0500		.0000	1.0000	.0217	.0000
	B	Lunar launch	.9527	.4675	.0472	None	.0000	1.0000	.0221	.0000
	C		.9524	.4658	.0476		.0000	1.0000	.0222	.0000
	D		.9156	.3998	.0844		.0000	1.0000	.0338	.0000
13	A		.9500	.4123	.0500		.0000	1.0000	.0206	.0000
	B	Lunar orbit escape	.9528	.4454	.0472	None	.0000	1.0000	.0210	.0000
	C		.9524	.4436	.0476		.0000	1.0000	.0211	.0000
	D		.9522	.3661	.0478		.0000	1.0000	.0175	.0000
14	A		.9088	.3917	.0912		.0000	1.0000	.0357	.0000
	B	Midcourse	.9104	.4243	.0896	None	.0000	1.0000	.0380	.0000
	C		.9104	.4225	.0896		.0000	1.0000	.0378	.0000
	D		.9104	.3486	.0896		.0000	1.0000	.0312	.0000
15	A		.9816	.3560	.0184		.9890	.0110	.0001	.0065
	B	Transearth coast	.9824	.3863	.0175	CM A/C + 16	.9971	.0029	.0000	.0068
	C		.9807	.3846	.0193		.9930	.0070	.0001	.0074
	D		.9798	.3173	.0202		.9918	.0082	.0001	.0064
16	A		.9900	.3495	.0100		.0000	1.0000	.0035	.0000
	B	Earth entry and landing	.9981	.3795	.0019	None	.0000	1.0000	.0007	.0000
	C		.9940	.3772	.0060		.0000	1.0000	.0023	.0000
	D		.9928	.3109	.0072		.0000	1.0000	.0022	.0000
	A		.3460							
	B	Nominal mission probability	.3788							
	C		.3749							
	D		.3087							
	A		.0126							
	B	Abort success probability	.0097							
	C		.0105							
	D		.0095							
	A		.3586							
	B	Mission success probability	.3885							
	C		.3855							
	D		.3182							

		Abort Safety Failure Probability		Abort Success Probability After Lunar Landing
$\sum =$	A	.1432	A	.0126
	B	.1322	B	.0097
	C	.1365	C	.0105
	D	.1549	D	.0095
Crew safety =	A	.8568		
	B	.8678		
	C	.8635		
	D	.8451		

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TABLE V-4

LOR Estimated Reliability and Crew Safety (Equipment and Meteoroid Hazard)

		Steps	Estimated Reliability	Probability of Reaching Step	Abort Probability	Abort Mode Steps	Abort System Reliability	Abort System Unreliability	Abort System Failure Probability: LEM CM Lost	Abort System Failure Probability: LEM Only Lost	Abort Success Probability for Two Men After Lunar Landing
1	A	First stage (no engine out)	.8778	1.0000	.1222	Tower + 20	.9890	.0110	.0013	.0013	
	B		.8778	1.0000	.1222		.9971	.0029	.0304	.0004	
	C		.8778	1.0000	.1222		.9930	.0070	.0008	.0008	
	D		.8778	1.0000	.1222		.9930	.0070	.0008	.0008	
2	A	Second stage (no engine out)	.8302	.8778	.1698	SM - A + 20	.9594	.0406	.0060	.0060	
	B		.8302	.8778	.1698		.9672	.0327	.0049	.0049	
	C		.8302	.8778	.1698		.9633	.0367	.0055	.0055	
	D		.8302	.8778	.1698		.9632	.0367	.0055	.0055	
3	A	Earth orbit coast	.9988	.7287	.0011	SM A + 18 + 19 + 20	.9594	.0406	.0000	.0000	
	B		.9998	.7287	.0002		.9672	.0328	.0000	.0000	
	C		.9997	.7287	.0003		.9632	.0368	.0000	.0000	
	D		.9997	.7287	.0003		.9091	.0909	.0000	.0000	
4	A	Third stage (2 burns)	.8644	.7279	.1356	SM A + 18 + 19 + 20	.9049	.0951	.0094	.0094	
	B		.8644	.7286	.1356		.9147	.0853	.0084	.0084	
	C		.8644	.7286	.1356		.9093	.0907	.0090	.0090	
	D		.8644	.7286	.1356		.9092	.0908	.0090	.0090	
5	A	LEM transfer	.9900	.6292	.0100	SM A + 18 + 19 + 20	.9049	.0951	.0006	.0006	
	B		.9952	.6298	.0048		.9147	.0853	.0002	.0002	
	C		.9952	.6298	.0048		.9093	.0907	.0003	.0003	
	D		.9903	.6298	.0097		.9092	.0908	.0006	.0006	
6	A	Midcourse	.9460	.6229	.0540	SM - A + 18 + 19 + 20	.9049	.0951	.0032	.0032	
	B		.9477	.6268	.0523		.9147	.0853	.0028	.0028	
	C		.9477	.6268	.0523		.9093	.0907	.0030	.0030	
	D		.9477	.6237	.0523		.9092	.0908	.0030	.0030	
7	A	Translunar coast	.9878	.5893	.0122	SM - A + 18 + 19 + 20	.9049	.0951	.0007	.0006	
	B		.9886	.5940	.0113		.9147	.0853	.0006	.0006	
	C		.9869	.5940	.0131		.9093	.0907	.0007	.0007	
	D		.9869	.5910	.0131		.9092	.0908	.0007	.0007	
8	A	Lunar orbit retro	.9691	.5821	.0309	SM - A + 18 + 19 + 20	.9049	.0951	.0017	.0017	
	B		.9718	.5873	.0282		.9147	.0853	.0014	.0014	
	C		.9714	.5862	.0286		.9093	.0907	.0015	.0015	
	D		.9714	.5833	.0286		.9092	.0908	.0015	.0015	
9	A	Lunar orbit coast	.9988	.5641	.0012	SM - A + 18 + 19 + 20	.9049	.0951	.0001	.0001	
	B		.9996	.5707	.0004		.9147	.0853	.0000	.0000	
	C		.9995	.5694	.0004		.9095	.0907	.0002	.0002	
	D		.9946	.5666	.0054		.9092	.0908	.0003	.0003	
10	A	LEM separation	.9891	.5634	.0109	Dock + 17 + 18 + 19 + 20	.8778	.1222	.0008	.0002	
	B		.9976	.5705	.0023		.8897	.1103	.0004	.0002	
	C		.9969	.5691	.0031		.8841	.1159	.0002	.0002	
	D		.9960	.5635	.0040		.8840	.1160	.0002	.0002	
11	A	CM orbit coast	.9990	.5572	.0010	15 + 16 + 17 + 18 + 19 + 20	.8753	.1247	.0001	.0000	.0054
	B		.9999	.5691	.0001		.8900	.1100	.0000	.0000	.0012
	C		.9999	.5674	.0001		.8838	.1162	.0000	.0000	.0016
	D		.9987	.5613	.0012		.8674	.1326	.0001	.0000	.0006
12	A	Descent to moon	.9691	.5567	.0309	15 + 16 + 17 + 18 + 19 + 20	.8753	.1247	.0021	.0006	
	B		.9718	.5691	.0282		.8900	.1100	.0018	.0005	
	C		.9714	.5673	.0286		.8838	.1162	.0019	.0005	
	D		.9711	.5606	.0289		.8674	.1326	.0021	.0008	
13	A	Landing on moon	.8921	.5395	.1079	15 + 16 + 17 + 18 + 19 + 20	.8753	.1247	.0072	.0019	
	B		.9415	.5530	.0585		.8900	.1100	.0036	.0010	
	C		.9415	.5511	.0585		.8838	.1162	.0037	.0010	
	D		.8850	.5444	.1150		.8674	.1326	.0083	.0030	
14	A	Lunar operations	.9877	.4813	.0123	15 + 16 + 17 + 18 + 19 + 20	.8753	.1247	.0007	.0002	.0052
	B		.9975	.5207	.0025		.8900	.1100	.0001	.0000	.0012
	C		.9968	.5188	.0032		.8838	.1162	.0002	.0000	.0015
	D		.9968	.4818	.0032		.8674	.1326	.0002	.0001	.0013
15	A	Lunar launch	.9691	.4754	.0309	None	.0000	1.0000	.0147	.0147	.0000
	B		.9718	.5194	.0282		.0000	1.0000	.0147	.0146	.0000
	C		.9714	.5171	.0286		.0000	1.0000	.0148	.0148	.0000
	D		.9543	.4801	.0457		.0000	1.0000	.0220	.0220	.0000
16	A	Lunar rendezvous and docking	.9392	.4607	.0608	16A + 17 + 18 + 19 + 20	.8769	.1230	.0034	.0034	.0246
	B		.9444	.5047	.0556		.8913	.1087	.0030	.0030	.0250
	C		.9444	.5023	.0556		.8832	.1167	.0033	.0033	.0247
	D		.9173	.4583	.0827		.8832	.1168	.0044	.0044	.0335
17	A	Lunar orbit escape	.9691	.4327	.0309	None	.0000	1.0000	.0134	.0134	.0000
	B		.9718	.4766	.0282		.0000	1.0000	.0134	.0134	.0000
	C		.9714	.4744	.0286		.0000	1.0000	.0136	.0136	.0000
	D		.9714	.4204	.0286		.0000	1.0000	.0120	.0120	.0000
18	A	Midcourse	.9460	.4193	.0540	None	.0000	1.0000	.0226	.0226	.0000
	B		.9477	.4632	.0523		.0000	1.0000	.0242	.0242	.0000
	C		.9477	.4608	.0523		.0000	1.0000	.0241	.0241	.0000
	D		.9477	.4084	.0523		.0000	1.0000	.0214	.0214	.0000
19	A	Transearth coast	.9970	.3966	.0030	CM AC + 20	.9890	.0110	.0000	.0000	.0012
	B		.9979	.4390	.0021		.9971	.0029	.0000	.0000	.0009
	C		.9961	.4367	.0039		.9930	.0070	.0000	.0000	.0017
	D		.9960	.3870	.0040		.9930	.0070	.0000	.0000	.0015
20	A	Earth entry and landing	.9900	.3955	.0100	None	.0000	1.0000	.0039	.0039	.0000
	B		.9981	.4380	.0019		.0000	1.0000	.0008	.0008	.0000
	C		.9940	.4350	.0060		.0000	1.0000	.0026	.0026	.0000
	D		.9940	.3854	.0060		.0000	1.0000	.0023	.0023	.0000
	A	Nominal mission probability	.3915					∑ = A	.0921	.0841	.0363
	B		.4372					B	.0806	.0766	.0283
	C		.4324					C	.0854	.0811	.0294
	D		.3831					D	.0945	.0876	.0370
	A	Abort success probability	.0363								
	B		.0283								
	C		.0294								
	D		.0370								
	A	Mission success probability	.4278					A	.9078	.9159	
	B		.4655					Crew safety = B	.9194	.9234	
	C		.4618					C	.9146	.9189	
	D		.4201					D	.9055	.9124	

[redacted]

TABLE V-5

Meteoroid Penetration Probability--Two-Man DF

Step and Duration in Hr	Equipment Failure Probability x 10^{-6}: CM	H_2 Tank TO	O_2 Tank (4)	H_2 Landing	O_2 Landing (4)	Super CO_2	Super H_2	Super N_2	Glycol	He	FCB	Radiator, Environment Control	Radiator, FCB	Total	Probability of no Meteoroid Penetration During Mission Phase: Meteor R	Probability of No Meteoroid Penetration x Equipment Reliability for Mission Phase, Table V-3: A	B	C	D
Earth orbit coast 1.5	2	30	29	71	66	--	2	--	1	--	10	--	--	211	.99978900	.99879221	.99971074	.99967179	.99964070
Third stage burn .01	--	--	--	--	--	--	--	--	--	--	--	--	--	--	1.0000	.864400	.864400	.864400	.86432382
Midcourse .02	--	--	--	2	2	--	--	--	--	--	--	--	--	4	.99999600	.90880336	.91044280	.91041597	.90890006
Translunar coast 70	165	2800	2720	6,580	6,130	4	81	18	27	5	402	4	2	18,938	.98124100	.98027938	.98112690	.97936078	.97930952
Lunar orbit retro .07	--	1	1	3	3	--	--	--	--	--	--	--	--	8	.99999200	.95004040	.95276025	.95236214	.95232373
Lunar orbit coast 4	5	80	77	188	176	--	3	1	1	--	11	--	--	542	.99945800	.99845854	.99931972	.99923182	.97868962
Descent to moon .12	--	2	2	5	5	--	--	--	--	--	--	--	--	14	.99998600	.95003470	.95275387	.95237894	.95109085
Landing on moon .02	--	--	--	1	1	--	--	--	--	--	--	--	--	2	.99999800	.87447425	.92313708	.92308330	.81156432
Lunar operations 48	57	960	927	3,290	2,120	1	33	6	9	1	138	1	2	7,545	.99248340	.98259727	.99237165	.99166691	.99166676
Lunar launch .13	--	3	3	6	6	--	--	--	--	--	--	--	--	18	.99998200	.95003090	.95274690	.95236081	.91557015
Lunar orbit escape .02	--	--	--	1	1	--	--	--	--	--	--	--	--	2	.99999800	.95004610	.95276594	.95236786	.95223373
Midcourse .02	--	--	--	2	2	--	--	--	--	--	--	--	--	4	.99999600	.90880336	.91044280	.91041597	.91036849
Transearth flight 65	153	2600	2520	6,120	5,690	4	75	17	25	4	374	4	2	17,588	.98256580	.98160288	.98245155	.98068305	.97978093
Earth entry and landing	--	--	--	--	--	--	--	--	--	--	--	--	--	--	1.000	.99003300	.99809674	.99398505	.99276948
Total	382	6476	6279	16,269	14,202	9	194	42	63	10	935	9	6	44,876					

[redacted]

TABLE V-6

Meteoroid Penetration Probability--LOR/CSM

Step and Duration in Hr	Equipment Failure Probability x 10^{-6}													Probability of Meteoroid Penetration During Mission Phase	Probability of No Meteoroid Penetration x Equipment Reliability for Mission Phase for LOR/LEM and LOR/CSM			
	CM	Super C O_2	Super C H_2	Super C N_2	Accumulated Glycol	Aerozine	N_2O_4	N_2O_4	$He_{(2)}$	FCB	Radiator Environment Control	Radiator, FCB	Total		Table V-4 A	Table V-4 B	Table V-4 C	Table V-4 D
Earth orbit coast 1.5	7	--	2	--	1	12	3	1	--	10	--	--	36	.999854	.9885714	.99977573	.99973677	.99973677
Third stage burn .01	--	--	--	--	--	--	--	--	--	--	--	--	--	1.000	.86440000	.86440000	.86440000	.86440000
LEM trans .03	--	--	--	--	--	--	--	--	--	--	--	--	--	1.000	.99002800	.99524334	.99524266	.99033321
Midcourse .02	--	--	--	--	--	--	--	--	--	--	--	--	--	1.000	.94598300	.94769442	.94766650	.94766638
Translunar flight 70	610	4	81	18	27	535	405	67	5	402	4	2	2160	.98877450	.98780550	.98865952	.98687985	.98687983
Lunar orbit retro .07	--	--	--	--	--	--	--	--	--	--	--	--	--	1.000	.96910100	.97179252	.97138646	.97137500
4	17	--	3	1	1	15	12	2	--	11	--	--	62	.999763	.99876324	.99962468	.99953675	.99460890
CM coast 48	210	1	33	6	9	181	139	23	1	138	1	2	744	.999046	.98907252	.99765075	.99688370	.99604618
LEM separation .02	--	--	--	--	--	--	--	--	--	--	--	--	--	1.000	.99900000	.99986177	.99986068	.99874845
Descent to moon .12	1	--	--	--	--	1	1	--	--	--	--	--	3	.999985	.96908646	.97176639	.97138398	.97112573
Land on moon .02	--	--	--	--	--	--	--	--	--	--	--	--	--	.999998	.89212722	.94151867	.94146573	.88504832
Lunar operations 48	--	--	--	--	--	--	--	--	--	--	--	--	--	.99764480	.98770726	.99749455	.99678548	.99678513
Lunar launch .13	--	--	--	--	--	--	--	--	--	--	--	--	--	.999995	.96909615	.97176432	.97136984	.95428043
Lunar rendezvous and docks	4	--	--	--	--	4	4	--	--	3	--	--	15	.999933	.93917507	.94443203	.94440879	.91726189
Lunar orbit escape	--	--	--	--	--	--	--	--	--	--	--	--	--	1.000	.96910100	.97179252	.97138646	.97138580
Midcourse .02	--	--	--	--	--	--	--	--	--	--	--	--	--	1.000	.94598300	.94769442	.94766650	.94766582
Transearth flight 65	578	4	75	17	25	496	377	62	5	374	4	2	2019	.99798300	.99700498	.99786695	.99607071	.99597810
Earth entry and landing	--	--	--	--	--	--	--	--	--	--	--	--	--	1.0000	.99003300	.99809619	.99398450	.99396878
Total	1427	9	194	42	63	1244	941	155	11	938	9	6	5039					

[redacted]

TABLE V-7

Meteoroid Penetration Probability--LOR/LEM

Step and Duration in Hr	Equipment Failure Probability x 10^{-6}																					
	Crew Compartment C/M	N_2H_4	N_2O_4	H_2	N_2O_4	N_2H_4	N_2O_4	H_2O	H_2O	O_2	O_2	N_2O_4	N_2H_4	N_2H_4	O_2	H_E	H_E	H_E	N_2	H_e	Total LEM	Total LEM + CM + SM
Earth orbital coast 1.50	50	3	14	1	3	8	7	6	1	--	1	2	12	2	--	--	--	--	--	--	110	146
Third stage burn .01	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
LEM transfer 0.03	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Midcourse 0.02	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Translunar coast 69.5	3905	296	1260	84	284	818	346	510	77	43	60	159	1065	154	5	18	2	14	20	9	9,129	11,289
Lunar orbit retro 0.07	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Lunar orbit coast $.3^h$	67	5	27	1	4	15	15	10	1	1	1	3	22	3	--	--	--	--	--	--	175	237
LEM separation 0.02	1	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
CM coast 40^h	210	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	210	954
Descent to moon 0.12	5	--	2	--	--	1	1	1	--	--	--	--	2	--	--	--	--	--	--	--	12	15
Landing on moon 0.02	1	--	1	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	2	2
Lunar operations 43.0	1612	98	--	--	98	248	238	--	26	--	30	--	--	--	2	6	--	--	--	--	2,358	2,358
Lunar launch 0.13	5	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	5	5
Lunar rendezvous and docking 1.0	36	2	--	--	2	6	5	--	1	--	--	--	--	--	--	--	--	--	--	--	52	67
Lunar orbit escape 0.07	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Midcourse 0.02	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Transearth coast 65	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	2,019
Earth entry and landing	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Total	5892	404	1304	86	391	1096	612	527	106	44	92	164	1101	159	7	24	2	14	20	9	12,053	17,092

[redacted]

TABLE V-8

DF Base Reliability Values

	A	B	C	D
(1) First-Stage Boost				
Power (electric)	.999986		Same as A	
Environmental control system	.999997			
Fuel system	.996080			
Oxidizer system	.992280			
Hydraulic control (5 engines)	.990480			
Auxiliary power	1.000000			
Pneumatic control	.997580			
Electronics and guidance	.988180			
Airframe and separation	.998180			
Engines (5)	.911280			
Total	.877830			
(2) Second-Stage Boost				
Power (electric)	.999970		Same as A	
Environmental control system	.999994			
Fuel system	.997700			
Oxidizer system	.994400			
Hydraulic control system (5 engines)	.988400			
Auxiliary power	1.000000			
Electronics and guidance	.974400			
Airframe and separation	.998100			
Propellant utilization	.997500			
Engines (5)	.872700			
Total	.830170			

[redacted]

TABLE V-8 (continued)

	A	B	C	D
(3) Earth Orbit Coast				
Structures	.999961	.99996100	.99996100	.99996100
Attitude control	.999612	.99999998	.99999998	.99996820
Environmental control	.999857	.99999995	.99999995	.99999995
Power (electric)	.999876	.99999995	.99999995	.99999995
Display instrumentation	.999961	.99996100	.99996100	.99996100
Electronics and guidance	.999775	.99999996	.99996100	.99996100
Flight control	.999961	.99999996	.99999996	.99999996
Total	.999003	.99992172	.99988276	.99985167
(4) Third-Stage Boost (2 Burns)				
Power (electric)	.999922			.99990217
Environmental control	.999995			
Fuel system	.995663			
Oxidizer system	.989060			
Dual burn control (fuel)	.997883			
Dual burn control (oxidizer)	.998492			
Hydraulic control	.995473		Same as A	
Auxiliary power	1.000000			
Electronics and guidance	.965790			
Airframe and separation	.998203			.99813911
Propellant utilization	.995283			
Attitude control	.986090			
Roll control	.998372			
Engine	.947290			
Engine dual burn control	.989060			
Total	.864400	.864400	.864400	.86432381

TABLE V-8 (continued)

	A	B	C	D
(5) Midcourse Corrections				
Power (electric)	.999999	.99999996	.99999996	.99999996
Environmental control	.999999	.99999995	.99999995	.99999995
Electronics and guidance	.999300	.99999996	.99997050	.99997050
Attitude control	.999800	.99999994	.99999994	.99985189
Airframe	.999900	.99980000	.99980000	.99980000
Fuel system	.997800	.99560000	.99560000	.99408718
Oxidizer system	.994500	.98903025	.98903025	.98903250
Hydraulic control	.997700	.99540529	.99540529	.99540529
Propellant utilization	.997600	.99520576	.99520576	.99520576
Engine	.966200	.93354244	.93354244	.93354244
Total per maneuver	.953314	.91044644	.91041961	.90890370
2 maneuvers =	.908807			
(6) Translunar Coast				
Power (electric)	.999827	.99989071	.99989071	.99989071
Environmental control	.999800	.99999895	.99999895	.99999387
Attitude control	.999854	.99999498	.99999498	.99999477
Electronics and guidance	.999539	.99999908	.99819900	.99819900
Total	.999020	.99988372	.99808384	.99803159
(7) Lunar Orbit Retro				
Power (electric)	.999856	.99999973	.99999973	.99999837
Environmental control	.999882	.99999995	.99999995	.99999887
Electronics and guidance	.999301	.99999984	.99958200	.99958200
Attitude control	.999802	.99999998	.99999998	.99999809
Airframe and separation	.998210	.99821000	.99821000	.99821000
Fuel system	.997812	.99781200	.99781200	.99781200

TABLE V-8 (continued)

	A	B	C	D
(7) Lunar Orbit Retro (continued)				
Oxidizer system	.994513	.99451300	.99451300	.99451300
Hydraulic control	.997712	.99771200	.99771200	.99771200
Propellant utilization	.997613	.99761300	.99761300	.99761300
Roll control	.998303	.99999996	.99999996	.99996394
Engine	.966360	.96636000	.96636000	.96636000
Total	.950048	.95276787	.95236976	.95233135
(8) Lunar Orbit Coast				
Structure	.999863	.99986300	.99986300	.98002732
Attitude control	.999937	.99999998	.99999998	.99997846
Environmental control	.999838	.99999995	.99999995	.99999841
Power (electric)	.999803	.99999980	.99999980	.99999784
Instruments	.999999	.99999900	.99999900	.99999900
Electronics and guidance	.999620	.99999996	.99991200	.99920407
Flight controls	.999940	.99999996	.99999996	.99999880
Total	.999000	.99986165	.99977370	.97922036
(9) Descent to Moon				
Power (electric)	.999856	.99999899	.99999899	.99998688
Environmental control	.999882	.99999995	.99999995	.99999876
Electronics and guidance	.999301	.99999992	.99960640	.99830473
Attitude control	.999802	.99999996	.99999996	.99999791
Airframe and separation	.998210	.99821000	.99821000	.99821000
Fuel system	.997812	.99781200	.99781200	.99781200
Oxidizer system	.994513	.99451300	.99451300	.99451300
Hydraulic control	.997712	.99771200	.99771200	.99771200

TABLE V-8 (continued)

	A	B	C	D
(9) Descent to Moon (continued)				
Propellant utilization	.997613	.99761300	.99761300	.99761300
Roll control	.998303	.99999995	.99999995	.99996490
Engine	.966360	.96636000	.96636000	.96636000
Total	.950048	.95276721	.95239227	.95110417
(10) Landing on Moon				
Power (electric)	.999856	.99999995	.99999995	.99999920
Environmental control	.999882	.99999995	.99999995	.99999953
Electronics and guidance	.999301	.99999993	.99994370	.99994370
Attitude control	.999802	.99999998	.99999998	.99999887
Airframe and separation	.998210	.99821000	.99821000	.98720473
Fuel system	.997812	.99781200	.99781200	.99781200
Oxidizer system	.994513	.99451300	.99451300	.99451300
Hydraulic control	.997712	.99771200	.99771200	.99771200
Propellant utilization	.997613	.99761300	.99761300	.99761300
Roll control	.998303	.99999996	.99999996	.99999064
Engine	.966360	.96636000	.96636000	.96636000
Throttling controls	.968900	.96890000	.96890000	.96890000
Suitability of landing site	.950000	1.00000000	1.00000000	.88900000
Total	.874476	.92313706	.92308515	.81156594
(11) Lunar Operations				
Environmental control	.995800	.99999984	.99999984	.99999984
Power (electric)	.994913	.99998832	.99998832	.99998817
Instruments	.999900	.99990000	.99990000	.99990000
Guidance	.999400	.99999985	.99928970	.99928970
Flight controls	.999999	.99999939	.99999939	.99999931
Total	.990039	.99988740	.99917732	.99917718

TABLE V-8 (continued)

	A	B	C	D
(12) Lunar Launch				
Power (electric)	.999856	.99999656	.99999656	.99999431
Environmental control	.999882	.99999994	.99999994	.99999776
Electronics and guidance	.999301	.99999994	.99959470	.99856179
Attitude control	.999802	.99999911	.99999911	.99996040
Airframe and separation	.998210	.99821000	.99821000	.96074352
Fuel system	.997812	.99781200	.99781200	.99781200
Oxidizer system	.994513	.99451300	.99451300	.99451300
Hydraulic control	.997712	.99771200	.99771200	.99771200
Propellant utilization	.997613	.99761300	.99761300	.99761300
Roll control	.998303	.99999990	.99999990	.99993610
Engine	.966360	.96636000	.96636000	.96636000
Total	.950048	.95276405	.95237795	.91558663
(13) Lunar Orbit Escape				
Power (electric)	.999856	.99999973	.99999973	.99999815
Environmental control	.999882	.99999973	.99999973	.99999815
Electronics and guidance	.999301	.99999984	.99958200	.99948880
Attitude control	.999802	.99999998	.99999998	.99999241
Airframe and separation	.998210	.99821000	.99821000	.99821000
Fuel system	.997812	.99781200	.99781200	.99781200
Oxidizer system	.994513	.99451300	.99451300	.99451300
Hydraulic control	.997712	.99771200	.99771200	.99771200
Propellant utilization	.997613	.99761300	.99761300	.99761300
Roll control	.998303	.99999996	.99999996	.99996228
Engine	.966360	.96636000	.96636000	.96636000
Total	.950048	.95236976	.95236976	.95223563

[redacted]

TABLE V-8 (continued)

	A	B	C	D
(14) Midcourse Corrections				
Power (electric)	.999999	.99999996	.99999996	.99999998
Environmental control	.999999	.99999995	.99999995	.99999995
Electronics and guidance	.999300	.99999996	.99997000	.99997000
Attitude control	.999800	.99999994	.99999994	.99998672
Airframe	.999900	.99980000	.99980000	.99980000
Fuel system	.997800	.99560000	.99560000	.99560000
Oxidizer system	.994500	.98903025	.98903025	.98903025
Hydraulic control	.997700	.99540529	.99540529	.99540529
Propellant utilization	.997600	.99520576	.99520576	.99520576
Engine	.966200	.93354244	.93354244	.93354244
Total per maneuver	.953314	.91044644	.91041961	.91037213
2 maneuvers	.908807			
(15) Transearth Coast				
Power (electric)	.999827	.99989071	.99989071	.99979413
Environmental control	.999800	.99999895	.99999895	.99998854
Attitude control	.999854	.99999498	.99999498	.99979229
Electronics and guidance	.999539	.99999908	.99819900	.99758969
Total	.999020	.99988372	.99808344	.99716572
(16) Earth Entry and Landing				
Structure	.998250	.99825000	.99825000	.99825000
Attitude control	.999986	.99999988	.99999988	.99979099
Environmental control	.997500	.99999565	.99999565	.99991234
Power (electric)	.999676	.99986592	.99986592	.99986267
Electronics and guidance	.995300	.99999551	.99587600	.99500897
Flight controls	.999288	.99998960	.99998960	.99993234
Total	.990033	.99809674	.99396908	.99276948

[redacted]

TABLE V-9

LOR Base Reliability Values

	A	B	C	D
(1) First-Stage Boost				
Power (electric)	.999986			
Environmental control system	.999997			
Fuel system	.996080			
Oxidizer system	.992280			
Hydraulic control (5 engines)	.990480		Same as A	
Auxiliary power	1.000000			
Pneumatic control	.997580			
Electronics and guidance	.988180			
Airframe and separation	.998180			
Engines (5)	.911280			
Total	.877830	.877830	.877830	.877830
(2) Second-Stage Boost				
Power (electric)	.999970			
Environmental control system	.999994			
Fuel system	.997700			
Oxidizer system	.994400			
Hydraulic control system (5 engines)	.988400		Same as A	
Auxiliary power	1.000000			
Electronics and guidance	.974400			
Airframe and separation	.998100			
Propellant utilization	.997500			
Engines (5)	.872700			
Total	.830170	.830170	.830170	.830170

[redacted]

TABLE V-9 (continued)

	A	B	C	D
(3) Earth Orbit Coast				
Structures	.999961	.99996100	.99996100	.99996100
Attitude control	.999612	.99999998	.99999998	.99999998
Environmental control	.999857	.99999995	.99999995	.99999995
Power (electric)	.999876	.99999995	.99999995	.99999995
Display instrumentation	.999961	.99996100	.99996100	.99996100
Electronics and guidance	.999775	.99999996	.99996100	.99996100
Flight control	.999961	.99999996	.99999996	.99999996
Total	.999003	.99992172	.99988276	.99988284
(4) Third-Stage Boost (2 burns)				
Power (electric)	.999922	.99992200	.99992200	.99990217
Environmental control	.999995	.99999500	.99999500	.99999500
Fuel system	.995663	.99566300	.99566300	.99566300
Oxidizer system	.989060	.98906000	.98906000	.98906000
Dual burn control (fuel)	.997883	.99788300	.99788300	.99788300
Dual burn control (oxidizer)	.998492	.99849200	.99849200	.99849200
Hydraulic control	.995473	.99547300	.99547300	.99547300
Auxiliary power	1.000000	1.00000000	1.00000000	1.00000000
Electronics and guidance	.965790	.96579000	.96579000	.96579000
Airframe and separation	.998203	.99820300	.99820300	.99820300
Propellant utilization	.995283	.99528300	.99528300	.99528300
Attitude control	.986090	.98609000	.98609000	.98609000
Roll control	.998372	.99837200	.99837200	.99837200
Engine	.947290	.94729000	.94729000	.94729000
Engine dual burn control	.989060	.98906000	.98906000	.98906000
Total	.864400	.86440000	.86440000	.86440000

[redacted]

TABLE V-9 (continued)

	A	B	C	D
(5) LEM Transfer				
Power (electric)	.999999	.99999996	.99999996	.99999996
Environmental control system	.999999	.99999995	.99999995	.99999995
SIVB attitude control	.995070	.99999998	.99999998	.99507000
Airframe and separation	.999370	.99937000	.99937000	.99936800
Spacecraft attitude control	.999931	.99999994	.99999994	.99999900
Spacecraft electronics and guidance	.999760	.99999996	.99999923	.99999923
SIVB electronics and guidance	.995871	.99587100	.99587100	.99587100
Total	.990028	.99524339	.99524266	.99033321
(6) Midcourse Corrections (2 required)	1 Maneuver	2 Maneuvers	2 Maneuvers	2 Maneuvers
Power	.999999	.99999996	.99999996	.99999996
ECS	.999999	.99999999	.99999999	.99999999
Electronics and guidance	.999300	.99999996	.99997050	.99997050
Attitude control	.999800	.99999994	.99999994	.99999980
Airframe	.999900	.99980000	.99980000	.99980000
Fuel system	.996100	.99221521	.99221521	.99221521
Oxidizer system	.996100	.99221521	.99221521	.99221521
Hydraulic control	.998100	.99620361	.99620361	.96620361
Engine	.983100	.96648561	.96648561	.96648561
Total	.972617	.94769442	.94766650	.94766638
2 maneuvers = $.972617^2 = .945983$				
(7) Translunar Coast				
Power (electric)	.999827	.99989071	.99989071	.99989071
Environmental control	.999800	.99999895	.99999895	.99999893
Attitude control	.999854	.99999498	.99999498	.99999498
Electronics and guidance	.999539	.99999908	.99819900	.99819900
Total	.999020	.99988372	.99808384	.99808382

TABLE V-9 (continued)

	A	B	C	D
(8) Lunar Orbit Retro				
Power (electric)	.999905	.99999973	.99999973	.99999966
Environmental control	.999905	.99999995	.99999995	.99999894
Electronics and guidance	.999306	.99999984	.99958200	.99958200
Attitude control	.999806	.99999998	.99999998	.99999487
Airframe and separation	.998207	.99820700	.99820700	.99820700
Fuel system	.996109	.99610900	.99610900	.99610900
Oxidizer system	.996109	.99610900	.99610900	.99610900
Hydraulic control	.998107	.99810700	.99810700	.99810700
Roll control	.998307	.99999996	.99999996	.99999738
Engine	.983020	.98302000	.98302000	.98302000
Total	.969101	.97179252	.97138646	.97137500
(9) Lunar Orbit Coast				
Structure	.999863	.99986300	.99986300	.99986300
Attitude control	.999937	.99999998	.99999998	.99999982
Environmental control	.999838	.99999995	.99999995	.99999960
Power (electric)	.999803	.99999980	.99999980	.99999908
Instruments	.999999	.99999900	.99999900	.99999900
Electronics and guidance	.999620	.99999996	.99991200	.99991200
Flight controls	.999940	.99999996	.99999996	.99999976
Total	.999000	.99986165	.99977370	.99484469
(10) CM Orbit Coast				
Structure	.998630	.99863000	.99863000	.99863000
Attitude control	.999368	.99999969	.99999969	.99916412
Environmental control system	.998377	.99999984	.99999984	.99999753
Power (electric)	.998020	.99998832	.99998832	.99998692
Instruments	.999986	.99998600	.99998600	.99998600
Electronics and guidance	.996200	.99999985	.99923100	.99923100
Flight controls	.999399	.99999970	.99999970	.99999885
Total	.990017	.99860342	.99783564	.99699732

TABLE V-9 (continued)

	A	B	C	D
(11) LEM Separation				
Structure and separation	.999863	.99986300	.99986300	.99986300
Attitude control	.999937	.99999998	.99999998	.99999965
Environmental control	.999838	.99999995	.99999995	.99999911
Power (electric)	.999820	.99999993	.99999993	.99999901
Instruments	.999999	.99999900	.99999900	.99999900
Electronics and guidance	.999863	.99999995	.99999886	.99999886
Flight controls	.999940	.99999996	.99999996	.99888967
Total	.999000	.99986177	.99986068	.99874845
(12) Descent to Moon				
Power (electric)	.999905	.99998779	.99998779	.99998779
Environmental control	.999905	.99999995	.99999995	.99999948
Electronics and guidance	.999306	.99999992	.99960640	.99960640
Attitude control	.999806	.99999996	.99999996	.99975127
Airframe and separation	.998207	.99820700	.99820700	.99820700
Fuel system	.996109	.99610900	.99610900	.99610900
Oxidizer system	.996109	.99610900	.99610900	.99610900
Hydraulic control	.998107	.99810700	.99810700	.99810700
Roll control	.998307	.99999995	.99999995	.99998326
Engine	.983020	.98302000	.98302000	.98302000
Total	.969101	.97178097	.97139855	.97114030
(13) Landing on Moon				
Power (electric)	.999900	.99999979	.99999979	.99999852
Environmental control	.999900	.99999995	.99999995	.99999985
Electronics and guidance	.999300	.99999993	.99994370	.99909672
Attitude control	.999800	.99999998	.99999993	.99999698
Airframe and separation	.998200	.99820000	.99820000	.99820000
Fuel system	.996100	.99610000	.99610000	.99610000
Oxidizer system	.996100	.99610000	.99610000	.99610000
Hydraulic control	.998100	.99810000	.99810000	.99810000

[redacted]

TABLE V-9 (continued)

	A	B	C	D
(13) Landing on Moon (continued)				
Roll control	.998300	.99999996	.99999996	.96997525
Engine	.983000	.98300000	.98300000	.98300000
Throttling controls	.968900	.96890000	.96890000	.96890000
Suitability of landing site	.950200	1.00000000	1.00000000	.97000000
Total	.892129	.94152055	.94146760	.88505009
(14) Lunar Operations				
Environmental control	.995800	.99999984	.99999984	.99999948
Power (electric)	.994913	.99995032	.99995032	.99995032
Instruments	.999900	.99990000	.99990000	.99990000
Electronics and guidance	.999400	.99999985	.99928900	.99928900
Flight controls	.999999	.99999939	.99999939	.99999939
Total	.990039	.99984940	.99913865	.99913830

NOTE: The .9800 value in the chart includes both equipment reliability and probability of no meteoroid or radiation caused failures.

These are broken down as follows:

Equipment reliability = .9900 (same as orbiting CM). Probability of no meteoroid radiation abort = .9900 making the total .9800.

	A	B	C	D
(15) Lunar Launch				
Power (electric)	.999905	.99997576	.99997576	.99997576
Environmental control	.999905	.99999994	.99999994	.99999911
Electronics and guidance	.999306	.99999994	.99959400	.99959400
Attitude control	.999806	.99999990	.99999990	.99999820
Airframe and separation	.998207	.99820700	.99820700	.93067717
Fuel system	.996109	.99610900	.99610900	.99610900
Oxidizer system	.996109	.99610900	.99610900	.99610900
Hydraulic control	.998107	.99610700	.99610700	.99610700
Roll control	.998307	.99999990	.99999990	.99999990
Engine	.983020	.98302000	.98302000	.98302000
Total	.969101	.97176918	.97137469	.95428520

[redacted]

TABLE V-9 (continued)

	A	B	C	D
(16) Lunar Rendezvous and Dock				
Power (electric)	.999811	.99999988	.99999988	.99999838
Environmental control	.999811	.99999995	.99999995	.99999838
Electronics and guidance	.998575	.99999995	.99997535	.99997535
Attitude control	.999611	.99999998	.99999998	.99999667
Airframe	.996417	.99641700	.99641700	.99999411
Fuel system	.992236	.99223600	.99223600	.99223600
Oxidizer	.992236	.99223600	.99223600	.99223600
Hydraulic controls	.996217	.99621700	.99621700	.99621700
Roll control	.996618	.99999996	.99999996	.98814282
Engine	.966440	.96644000	.96644000	.96644000
Total	.939238	.94449531	.94447207	.91732335
(17) Lunar Orbit Escape				
Power (electric)	.999905	.99999973	.99999973	.99999954
Environmental control	.999905	.99999995	.99999995	.99999981
Electronics and guidance	.999306	.99999984	.99958200	.99958200
Attitude control	.999806	.99999998	.99999998	.99999957
Airframe and separation	.998207	.99820700	.99820700	.99820700
Fuel system	.996109	.99610900	.99610900	.99610900
Oxidizer system	.996109	.99610900	.99610900	.99610900
Hydraulic control	.998107	.99810700	.99810700	.99810700
Roll control	.998307	.99999996	.99999996	.99999760
Engine	.983020	.98302000	.98302000	.98302000
Total	.969101	.97179252	.97134646	.97138580
(18) Midcourse Corrections				
Power (electric)	.999999	.99999996	.99999996	.99999996
Environmental control	.999999	.99999995	.99999995	.99999995
Electronics and guidance	.999300	.99999996	.99999705	.99999705
Attitude control	.999800	.99999994	.99999994	.99999925
Airframe	.999900	.99980000	.99980000	.99980000

TABLE V-9 (continued)

	A	B	C	D
(18) Midcourse Corrections (continued)				
Fuel system	.996100	.99221521	.99221521	.99221521
Oxidizer system	.996100	.99221521	.99221521	.99221521
Hydraulic control	.998100	.99620361	.99620361	.99620361
Engine	.983100	.96648561	.96648561	.96648561
Total (per maneuver)	.972617	.94769442	.94766650	.94766582
Two maneuvers = $.972617^2$ = .945983				
(19) Transearth Coast				
Power (electric)	.999827	.99989071	.99989071	.99800910
Environmental control	.999800	.99999895	.99999895	.99999762
Attitude control	.999854	.99999498	.99999498	.99999314
Electronics and guidance	.999539	.99999908	.99819900	.99819900
Total	.999020	.99988372	.99808384	.99799104
(20) Earth Entry and Landing				
Structure	.998250	.99825000	.99825000	.99825000
Attitude control	.999986	.99999925	.99999925	.99998923
Environmental control	.997500	.99999565	.99999565	.99999115
Power (electric)	.999676	.99986592	.99986592	.99986592
Electronics and guidance	.995300	.99999551	.99587600	.99587600
Flight controls	.999288	.99998960	.99998960	.99998832
Total	.990033	.99809619	.99398450	.99396878

VI. RADIATION EXPOSURE COMPARISON

The radiation exposures calculated for use in this study and the physiological tolerances allowed are based on data provided in the NASA LEM RFP. Unshielded entrance doses resulting from the model flare are 7500 and 1310 rad for the LEM and CM, respectively. The inherent vehicle shielding capability was computed from the Martin Apollo study for the two-and three-man Command Modules. In each Command Module case a specific radiation shield weight allowance of 233 lb per man was used. The shielding characteristics of the LEM were computed from Martin's proposed design of the vehicle; no additional weight was allowed for specific radiation shielding.

The probability distributions of radiation incidence for each mode of operation are presented in Fig. VI-1 for the blood-forming organs and for the eyes.

The frequency of occurrence model in the LEM RFP indicates a flare of index intensity every 27.4 weeks (192 days). Taking the mission as a random 7.6-day event, the 100-rem exposure probability in the blood-forming organs is 0.0328 for the crew in the two-man DF vehicle, and also for the man who remains in the three-man LOR Command Module. For the two men who descend to the moon in the LEM the overall mission probability of receiving this dose is 0.0365. This difference could be further reduced if the LEM were provided with specific radiation shielding as permanent equipment or if part of the Apollo shielding were transferrable before descent. The 100-rem blood-forming organ dose is considered as the level below which no mission performance degradation should be expected.

It should be noted that before the 100-rem level is exceeded at the blood-forming organs, eye dosages in excess of the allowable 100-rem will be received, because of the greater eye exposure. Exceeding this dose will not degrade mission performance but will increase the probability of eye damage (mild cataracts) occurring in later years. The probability of 100-rem or greater eye dose is 0.072 for the LEM crewmen and 0.047 in either Command Module. Since the eye dose can be reduced with only a few pounds of shielding mass, eye exposure is not considered a significant factor in comparing the two configurations.

All the dosages were computed within the crew compartment in space. Regardless of the mode chosen, these doses will be reduced considerably on the lunar surface by the shielding (over $\sim 2\pi$ steradians) of the moon itself. The dosages may further be reduced by taking temporary shelter under the erected vehicle on the surface. The net effect of these alleviating factors would be both a reduction in dosage and a reduction in the relative dosages between the two modes.

Because of the small differences in performance-influencing exposure probabilities between the two modes, and the uncertainty regarding the amount of specific radiation shielding to be employed in the actual LEM, the probabilities of exceeding design dosage limits were not introduced into the overall system reliability analyses of Section V. In view of the payload growth margins included in the LOR and DF configurations, both modes can be considered equivalent from the standpoint of radiation as a factor affecting crew performance reliabilities.

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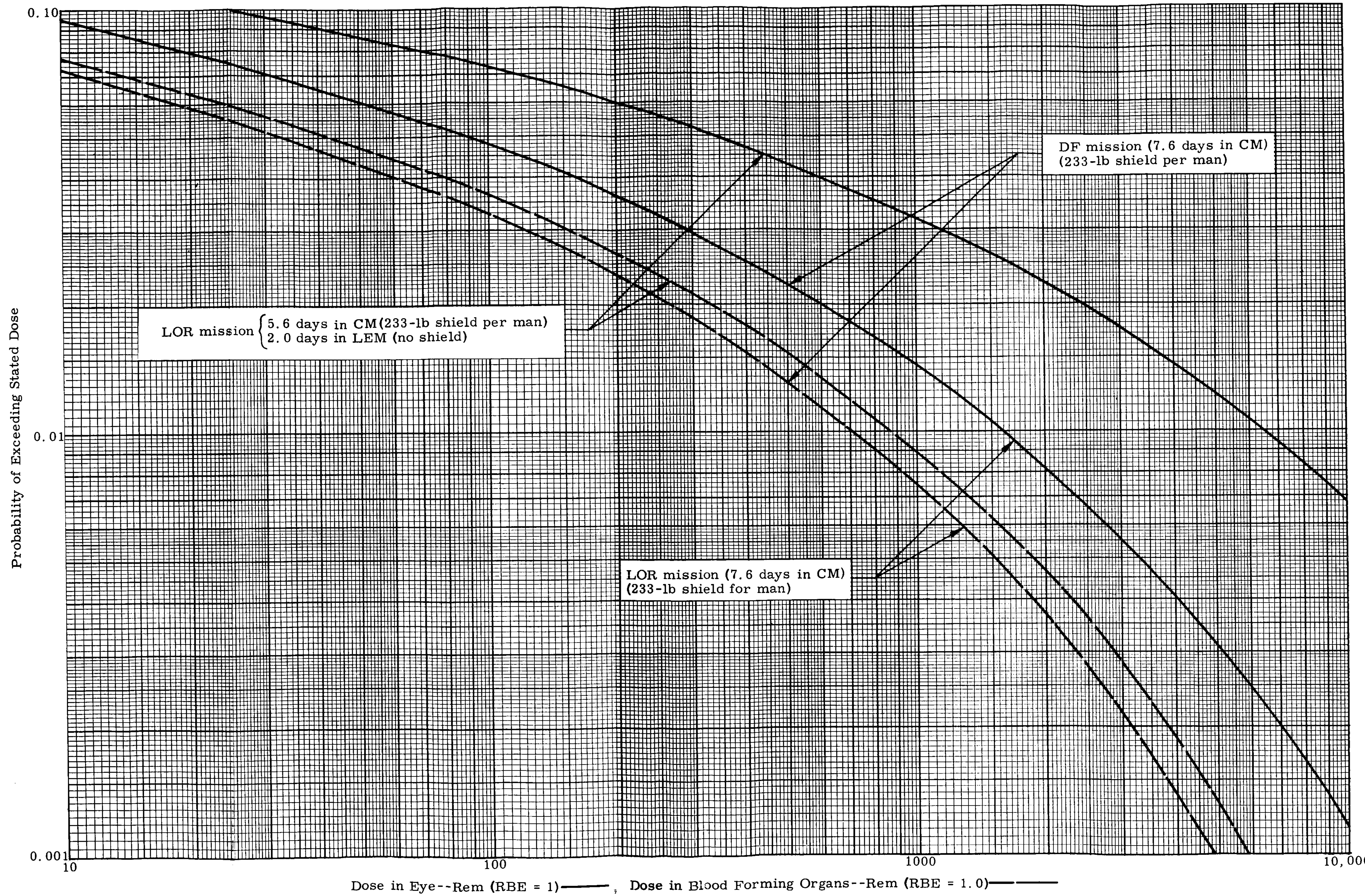

Fig. VI-1. Probability of Exceeding Stated Radiation Dosage

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VII. UNSCHEDULED MAINTENANCE CONSIDERATIONS

In the analyses reported in the foregoing sections, the crew functions considered include those in which man serves as a primary system, as a backup system, or--by switching from a failed system to an installed backup system--as a maintenance component.

Analyses of failure and repair possibilities and the effects of repair possibilities on mission success probability--such as the study reported in Ref. 21--indicate that there is another class of crew maintenance functions which for an appropriately configured system can result in a significant improvement in mission success probability. These functions take the form of module or component replacement or repair, and are highly dependent on the specific detailed configuration. For this reason, the influence of such unscheduled maintenance has not been included in the basic reliability or crew task analyses of the present study. The effect is potentially large, however, and must not be ignored completely.

Previous analysis of the Apollo/LEM in connection with the work reported in Ref. 21 has shown that, for a substantial number of failure possibilities, the addition of spares and tools can result in an appreciably higher reliability improvement than can the addition of an equivalent amount of weight for redundant subsystems and associated automatic or manual switching. For the present LOR and DF configurations, the systems were examined for maintainability during each phase of the mission. Time to repair, repair procedure, and parts availability were considered. It was found that 36 system failure/phase combinations in the DF mode and 51 in the LOR could be identified as maintainable. The differences result because of the reduced accessibility and spares availability associated with the more restricted volume of the DF Command Module, and also to a degree because of duplicate components in the LEM and the LOR Command Module.

A qualitative analysis was made of the reliability improvement afforded by consideration of these repair possibilities. An index of merit was used, computed by the following formula:

$$\text{Repair merit index} = 100 \left(\frac{R_R - R_{NR}}{1 - R_{NR}} \right)$$

where

R_R = reliability with repair (i.e., with the repaired unit considered as a redundancy)

R_{NR} = reliability with no repair

Significant differences were noted between the two modes, particularly for the environmental control system and the guidance system. Lesser differences were noted in the electrical, flight control, and display systems. In all cases the differences were markedly in favor of the LOR case, except for those phases of the mission subsequent to separation from the LEM for the return to earth; in this regime, retention of all onboard systems within the DF Command Module results in a very slight edge for the DF mode.

Consideration of possible repair in the event of meteoroid puncture would very significantly favor the LOR case. Access to the CM structure is quite limited in the DF; moreover, as shown in Section V, most of the penetration hazard for the DF is associated with the landing and service modules.

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